NASA CONTRACTOR REPORT

NASA CR-1361

STUDY OF A MODULAR EXTRAVEHICULAR ACTIVITY WORK PLATFORM

Prepared by
BENDIX CORPORATION
Mishawaka, Ind.

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1969

NASA CR-1361

STUDY OF A MODULAR EXTRAVEHICULAR ACTIVITY WORK PLATFORM

Distribution of this report is provided in the interest of information exchange. Responsibility for the contents resides in the author or organization that prepared it.

Issued by Originator as Report No. BMSD 6182

Prepared under Contract No. NASw-1820 by
BENDIX CORPORATION
Mishawaka, Ind.

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

ABSTRACT

This report presents results of studies to establish conceptual configurations for extravehicular activity (EVA) work platforms to be used by suited astronauts in orbital operations. The concept chosen consisted of a 1500 pound self-propelled EVA work platform made up of five modules which are removable and interchangeable to an extent permitting the orbital assembly of a mission oriented work platform. The scope of the study included a preliminary design of major subsystems and construction of a full scale mockup.

FOREWORD

This report was prepared by personnel of The Bendix Missile Systems Division, Mishawaka, Indiana, under Contract NASw-1820 with N.A.S.A. The report documents a study of a modular extra vehicular activity work platform performed by Bendix Missile Systems Division personnel under Contract #230673 with The Applied Physics Laboratory of Johns Hopkins University, Silver Spring, Maryland.

The study was performed by the Mechanical Engineering Department of BMSD with H. L. McClelland serving as project engineer. The following technical personnel, to whom acknowledgement is hereby made, conducted the study: J. M. Silvius and F. J. Peters, full time; L. G. Bach and F. M. Damico, part time. The report was prepared by the Mechanical Engineering department of BMSD with H. L. McClelland serving as project engineer. The following technical personnel, to whom acknowledgement is hereby made, prepared the report: J. M. Silvius, full time; F. J. Peters and L. G. DeGrace, part time.

Technical direction for the N.A.S.A. funded report was under Mr. W. L. Smith, N.A.S.A. OART Washington D.C. Technical direction for the APL/JHU funded study was under Mr. P. Iribe, APL/JHU Silver Spring, Maryland.

TABLE OF CONTENTS

ILLUSTRATIONS

TABLES

SECTION 1

SUMMARY

This report documents the efforts applied toward the conceptual design of a modularized EVA work platform. The purpose of the platform is to aid astronauts in EVA tasks originating from an orbiting space station. The study was limited to a modular, open platform concept. The modular construction was chosen because of apparent advantages in the following areas.

- Economy — Only those modules required by a given mission are used. Fuel is not expended in accelerating and decelerating unneeded systems.
- Stowage — Individual modules may be small and are therefore easy to handle and store.
- Service — Entire modules may be replaced by spare modules when servicing of the original module is required.

A detailed study comparing modular and non-modular devices, however, was beyond the scope of the project and was not performed.

As conceived the astronaut will conduct most of his work from the platform. He is equipped, however, with a Portable Life Support System (PLSS) so that he may leave the platform if he so desires.

The main module is the basic element of the EVA work platform. It provides a base from which an astronaut can perform work. The following systems are packaged in or on the main module:

- Propulsion
- Supplemental life support
- TV monitoring
- Communication
- Electrical power
- Illumination
- Worksite anchors
- Astronaut restraints
- Bilateral electrically powered manipulators

The propulsion system has the capability of producing approximately a 300 foot per second change in velocity to the main module when manned by a suited astronaut. The other systems are sized for a four-hour work period and a four-hour emergency period. Total weight of a fueled unmanned main module is approximately 800 pounds.

The total number of modules which can be used with the main module is unlimited but only four add-on modules are envisioned for use at any one time. Modules considered during the course of the project included:

- Extended Propulsion Capability
- Long Range Rendezvous
- Payload (tools, spare parts, test equipment, etc.)
- Extended Communications
- Rescue

A mockup of the configuration selected was built for purposes of concept and human factors evaluations.

SECTION 2

INTRODUCTION

This report presents the results of a study of conceptual configurations for Extra-Vehicular Activity (EVA) work platforms to be used in orbital operations by suited astronauts. The scope of the study included a preliminary design of major subsystems and construction of a full scale mockup.

The work platform configurations considered in this program were intentionally limited to open, modular, types, and no consideration of other types of astronaut EVA aids such as closed capsules or powered back packs was made. The ultimate goal of the project was to produce a logical concept of a modular EVA work platform, to develop a set of considerations for further detailed study of such a device, and to construct a mockup of the work platform to aid in future concept refinement and human factors studies. The chosen EVA work platform consists of a "main" module, containing the devices most likely to be required on most or all missions, to which can be added those other modules required for specific tasks or the extension of main module capabilities.

The intent of the platform is to provide a maneuverable, open base from which an astronaut could perform tasks in space, such as inspection and repair, and to provide him with assistance in the performance of such tasks. Modular construction permits the makeup of mission oriented work platforms to suit specific requirements of individual missions and offers several other advantages. They are:

- Fuel economy
- Versatility
- Stowage
- Capabilities
- Maintenance

Fuel economy is of considerable importance because of the very high cost of placing mass in orbit (approximately $250/lb). In the modular concept, a device or subsystem not needed on a given mission is not included in the platform assembly. The fuel that would have been expended to accelerate and decelerate the unneeded mass is thereby saved.

The use of the modular platform provides versatility by having the capability of adding or subtracting systems to match mission requirements. If a new system is needed for a particular task only that system need be designed or redesigned and adapted to the platform.

Stowage in orbit will be no problem, since it has been assumed that the work platform would be stowed or "parked" outside the home base station. However, stowage space on the supply vehicles from earth will be very precious. The ability to be easily broken down into components to fill relatively small available spaces is an advantage. The main module is ready for limited use as soon as it is placed in orbit and becomes more and more flexible and able as auxiliary modules become available.

Since the platform is open the astronaut is free to take part in the activity directly, should this be more convenient than using remote devices, or in the event of their failure. In this respect the concept allows maximum use of the capabilities of man in space.

Maintenance flexibility is maximized by modularization, since it is possible to remove all or part of a complete subsystem for repair or test. The unit under repair or test can be replaced with a similar unit, if needed, or if that module is not needed, the work platform can be used without it.

SECTION 3

GENERAL CONCEPT

Mission Analysis

Because no firm requirements exist at present for extra vehicular activity missions, several possibilities were chosen rather arbitrarily to be used as a basis around which to develop the modular EVA work platform concept. It should be stressed that these missions are hypothetical and do not reflect any present known planning. While these missions are only possibilities they highlight the ability of the modular concept to be adapted to a wide variety of orbital operations.

Assumptions

General Use. The basic purpose of the work platform is to provide a maneuverable, open base from which an astronaut could perform tasks in space and to provide him with assistance in the performance of such tasks. It is expected that simple inspection missions within very short distances of the mother ship, such as inspection of the station's exterior, would require a less sophisticated vehicle to move the astronaut about.

Operational Range Limitations. Because the work platform is a relatively small vehicle with limited propulsion capabilities, even in a maximum range configuration, its useful range will be generally limited to a relatively small region surrounding the orbiting home base. It is not capable of more than the slight orbital adjustments required to go from place to place within this region nor is it capable of rendezvous with objects passing through or nearby in other orbits. Hence, the area of operational usefulness for this and all similar devices seems to be rather clearly limited to clusters of devices, machines, laboratories, etc., more or less station keeping with a central home base space station.

Guidance. With the relatively severe restrictions on operational range, it would appear at first glance that electronic guidance assistance would not be required. However, in space such a cluster might be from 10 to 100 miles in diameter. (It seems reasonable to assume that if separation is required at all, relatively large separations might be involved.) In some instances, such as for a radio telescope, such distances from the base station might be mandatory. Distances of these magnitudes will present serious problems to the astronaut on his way to the outlying parts of the cluster, and rapid solutions to the orbital mechanic's problems involved will require electronic assistance.

To simplify the demands on the platform and the man, it has been assumed that each major object in the cluster has been equipped with an electronically identifiable transponder. This assumption seems reasonable, since each part of the cluster will have been intentionally placed there. The purpose of the transposers is to identify for the radar the object in its "field of vision" of interest to the astronaut.

Communications. A minimum communication capability of two voice radio channels between the astronaut and his base is considered mandatory, since it is the minimum possible means of maintaining a link between the two. Most of the purposes and needs for maintaining such a link are obvious. However, one special need is that it is the only practical means for the astronaut to record data visually obtained.

Mission Objectives and Requirements

Four basic types of work were considered feasible for man in the environment and circumstances assumed for this study. They are:

- Inspection of distant objects in the cluster
- Servicing
- Construction and assembly
- Structural repairs

Inspection. Two basic types of inspection missions can be anticipated to occur frequently in a community of orbiting objects. Simple visual inspection of the condition of the exterior for signs and/or locations of structural damage, particularly remotely controlled devices such as a large telescope, would be the most common type. The other would be inspection in which measurements would be required.

In the first case, capability for relatively long range navigation, propulsion, and large quantities of life support consummables was considered to be required since it has already been assumed that pure inspection missions of short range would be done with simpler devices. Since the object being inspected will always have random shadows cast upon it, artificial lighting must be provided for observation. Capability of transmitting television pictures to the home base or to earth to provide visual data to specialists may also be useful. Short range maneuverability is required to allow the astronaut to place himself in the best positions for observations. It may also be advantageous to be able to "park" the platform by docking it and then move about the object to be inspected by hand or with a hand held thruster. A transponder on the platform is considered mandatory for tracking by the mother ship.

For inspections requiring measurements, special instruments, tools, and a means to carry them will be required in addition to the basic equipment above. For this type of work, it is expected that docking capability would be required.

Servicing. Occasional and/or regular servicing of various components of orbiting devices were considered as possible missions, particularly in connection with remotely operated devices. Certain types of equipment, such as cameras and recording devices may also need periodic retrieval and replenishment of film and recording media. Such activity is considered to be limited to the direct replacement of functional modules or supply canisters due to the low level of dexterity of a suited astronaut. Simple adjustments may be made where provisions have been made for external access and delicate motions are not demanded.

In such missions the astronaut will need a means of carrying replacement hardware and/or replenishment supplies. He may or may not need long range operations capabilities, but will almost certainly need a stable platform to support reactions to his physical labors. Since some of the items that could conceivably require replacement could be thermally or radioactively "hot", some means should be available for remote handling (i.e., manipulators). As in inspection missions, illumination will be required for operations in shadows.

Construction or Assembly. One of the tasks of man in space is likely to be the construction of large complex facilities such as optical and radio telescopes, space stations, laboratories, manufacturing facilities, etc. Such operations will likely involve the assembly of large prefabricated subsections to eliminate the need for the manual dexterity required in detailed assembly. However, such a mode of construction requires relatively large amounts of propulsive power applicable with a high degree of directional control to provide for the gentle maneuvering of these massive subsections into position. A means will be required of providing a fixed position relative to at least one of the major subassemblies during the joining operation to provide reaction for forces required to achieve fine adjustments in positions between the two. Lighting will be necessary for the work involved in the joining operation, such as the installation of seals and fasteners.

Structural Repairs. It is conceivable that repairs to vehicle structures may be necessary. Such activities would require an anchored platform for absorbing reactive forces, a system for docking (including a control system for delicate translitory and attitude movements), tools and materials for the repair work, illumination, and propulsion.

Capabilities which may or may not be necessary for this type of operation, depending on the distance to the repair point, are extended range propulsion and guidance, and extra life support consummables. Television cameras to allow technical experts on earth or at the orbiting home base to observe and instruct the astronauts may be highly desirable. The capability to remotely handle thermally or radioactively "hot" items under repair should be available. The ability to be able to transport large objects, such as a large panel, would be useful, if not mandatory.

Overall Requirements. Having specified the general capabilities which should be contained in an EVA work platform, those common to all or most missions were segregated from the special purpose and "highly desirable" categories. Those required for all or most missions determined the requirements of the basic or "main" module of the concept. The remaining features then make up a list of special modules which can be added singly or in combination to achieve particular missions. Figure 1 illustrates the results.

MAIN MODULE

ALL MISSIONS

- PROPULSION
- ATTITUDE CONTROL
- COMMUNICATION
- ILLUMINATION
- RESTRAINTS
- LIFE SUPPORT CONSUMMABLES

MOST MISSIONS

- PLATFORM ANCHORS
- REMOTE HANDLING DEVICE

OTHER MODULES

LONG RANGE GUIDANCE

PAYLOAD

- TOOLS
- RESCUE GEAR
- INSTRUMENTS
- PERSONAL MANEUVERING DEVICE
- REPLENISHMENT/REPAIR MAT'LS

ADDITIONAL PROPULSION

TELEMETRY

Figure 1. Requirement Groupings for Modules

The other modules represent only those which were looked at during the course of this brief program. The concept itself implies that many others will be developed as requirements for orbital EVA missions become better defined. See Figure 2 for the four modules that were included in the mockup and figure 3 for the assembled work platform.

Main Module

The main module is the minimum element of the EVA work platform. It provides the astronaut with a means of transportation and with a stable platform from which to perform his tasks once the destination is reached. Manipulators are provided to assist the astronaut in docking and serve as arm extensions or extra arms after docking is achieved. Three work site anchors are available to tie the work platform to work site.

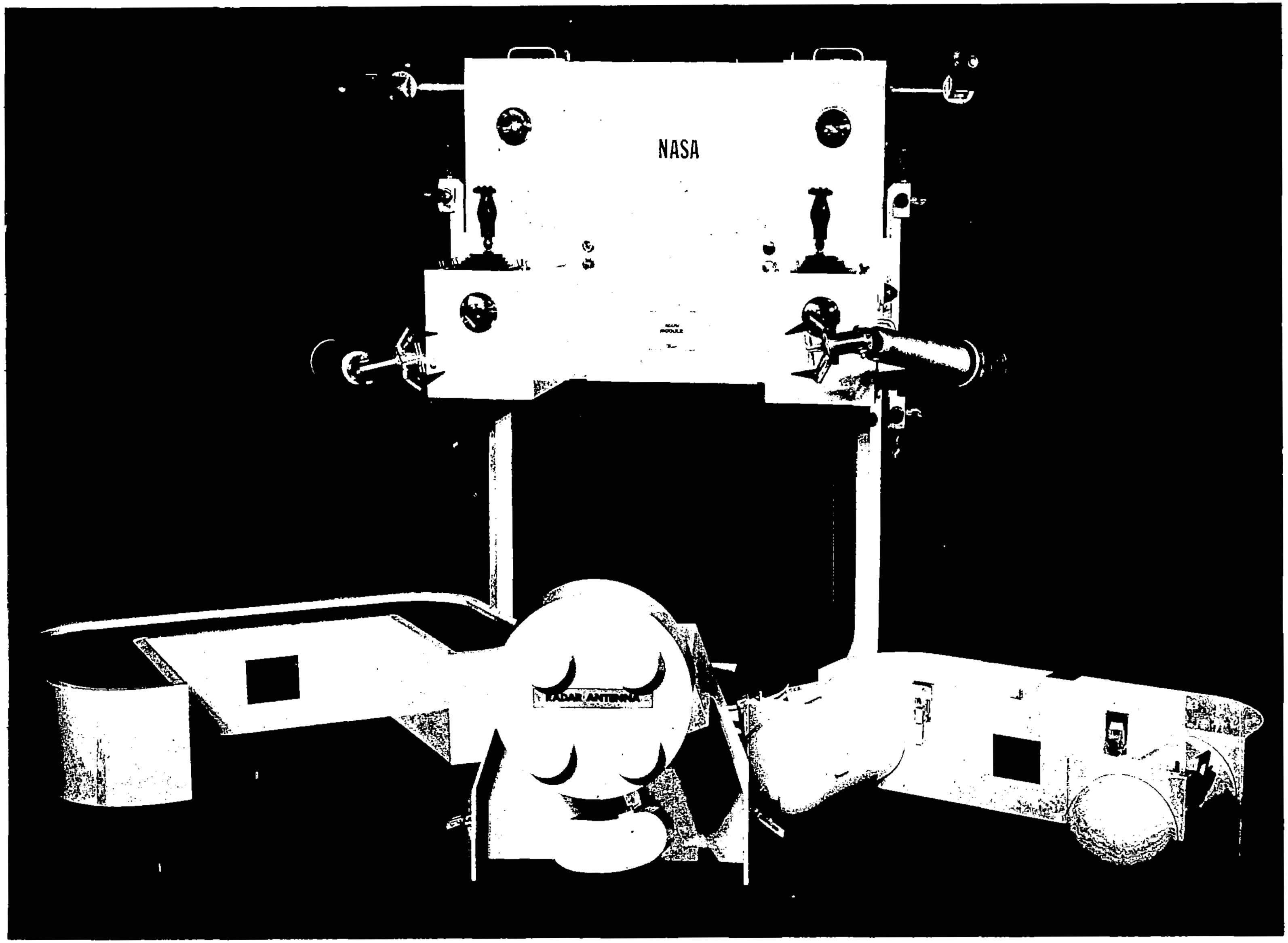


Figure 2. Main Module, Payload Module, Long Range Rendezvous Module and Extended Propulsion Capability Module

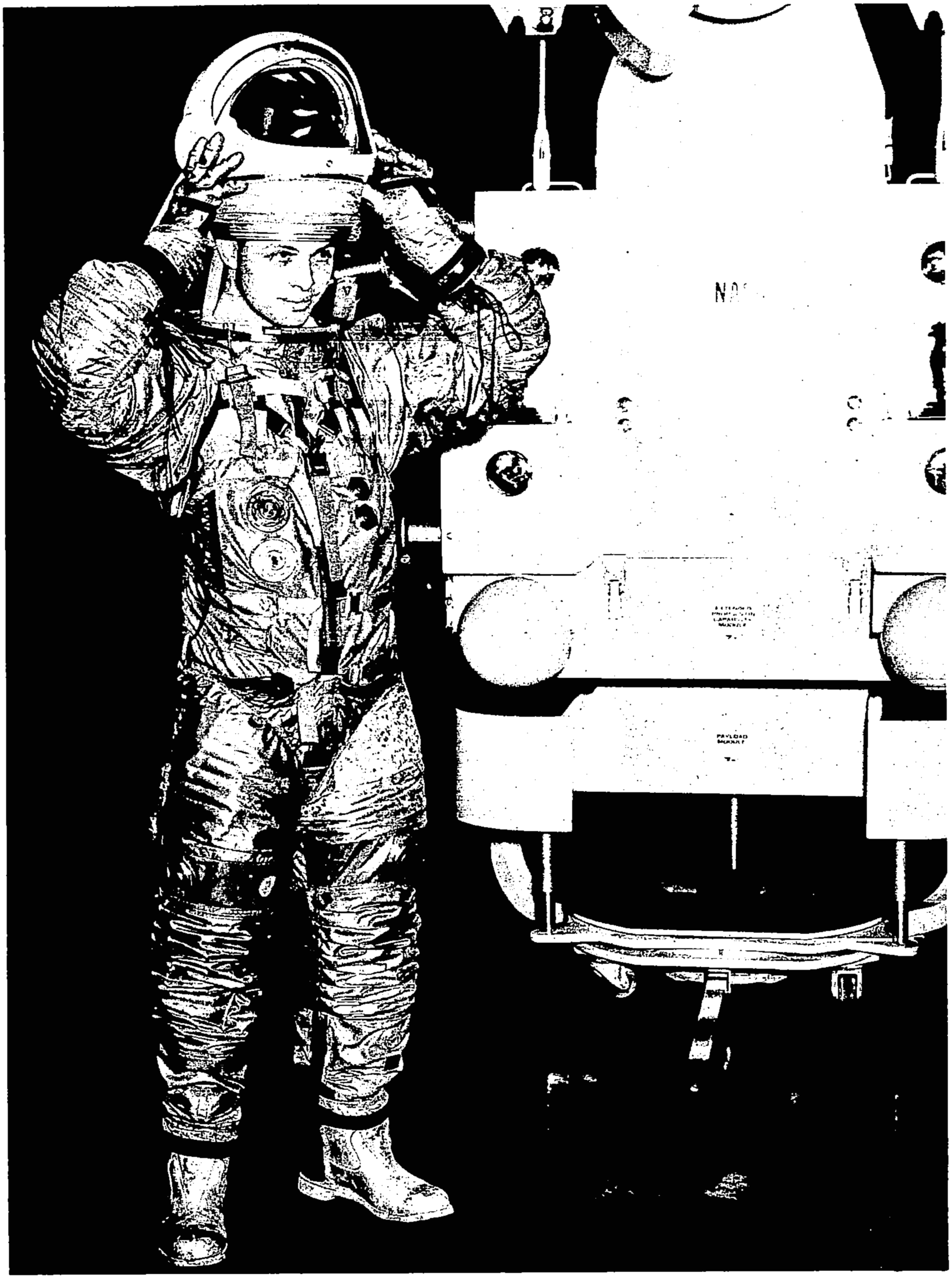


Figure 3. EVA Work Platform

Also included in the main module is a life support system which supplements the consummables contained in the astronaut's portable life support system (PLSS), a communications system that includes TV monitoring as well as voice transmission and receiving capabilities, illumination aids, and a transponder to aid the mother ship in tracking the work platform.

Total weight of the platform including the suited astronaut is estimated to be 1052 pounds. Overall dimensions of the module are given on Figure 4. A photograph of a mockup of the main module is shown in Figure 5. Figure 6 depicts an astronaut controlling the manipulators.

Long Range Rendezvous Module

The conceptual design of the modular EVA work platform includes a Long Range Rendezvous Module for use on missions requiring a travel in excess of 10,000 feet. The guidance system is patterned after the one used in Gemini. A transponder is required aboard the target vehicle to respond to interrogation by the work platform radar. This combination of interrogation and transponder offers the advantage of long range tracking with only relatively low transmitter power and without the need for highly sensitive and sophisticated receivers. The transponder reply is shifted in frequency from the transmitted signal to enable the receiver to differentiate between the desired transponder signal and unwanted primary echo returns at the interrogation frequency.

The radar employs three radome-covered spiral antennas for receiving and one spiral antenna for transmitting. An interferometer technique is used to determine azimuth and elevation angles. Range and range rate are also provided by the radar. The four antennas and their ground plane are placed over the astronaut's head and as far forward as necessary to avoid interference with the antenna patterns.

An instrument package for the astronaut is pivotable to allow as optimum as possible viewing when in use yet out of the way when not required (see Figures 7 and 8). It contains the radar range and range rate information as well as the so-called Q-ball which gives him the target bearings relative to his normal stabilization mode.

In the normally stabilized mode, the work platform is oriented vertically and facing the orbital track. It is anticipated that a computer packaged within the Long Range Rendezvous Module would use this information to determine the required propulsion direction and velocity change. The propulsion direction and the velocity change would be implemented automatically on command from the astronaut. The astronaut would resume autonomous propulsion control for a final docking maneuver.

The radar range is 250 miles. The interrogator radar requires about 40 watts of electrical power. A silver zinc battery is packaged within the module to serve the radar and computer.

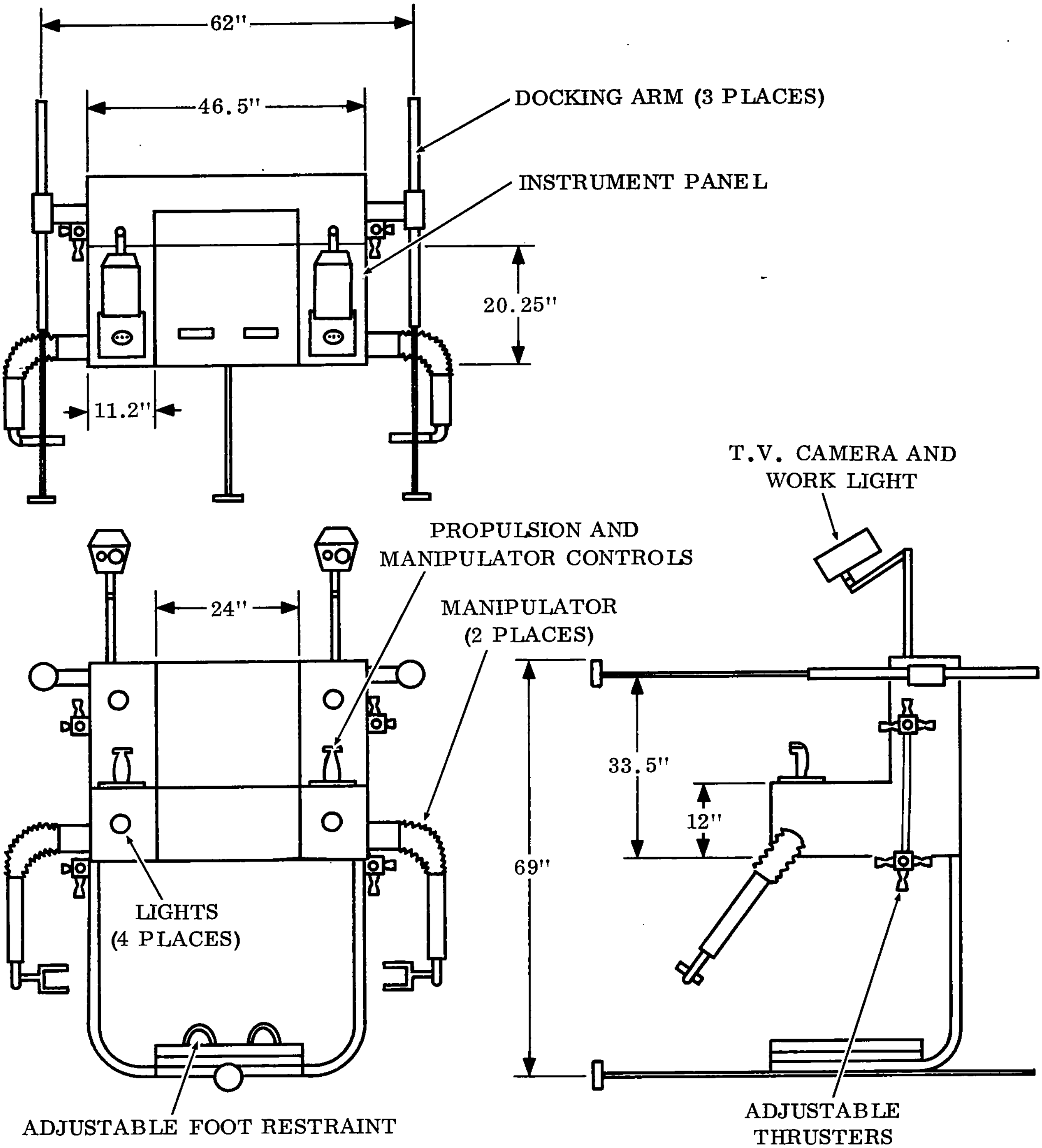


Figure 4. Main Module

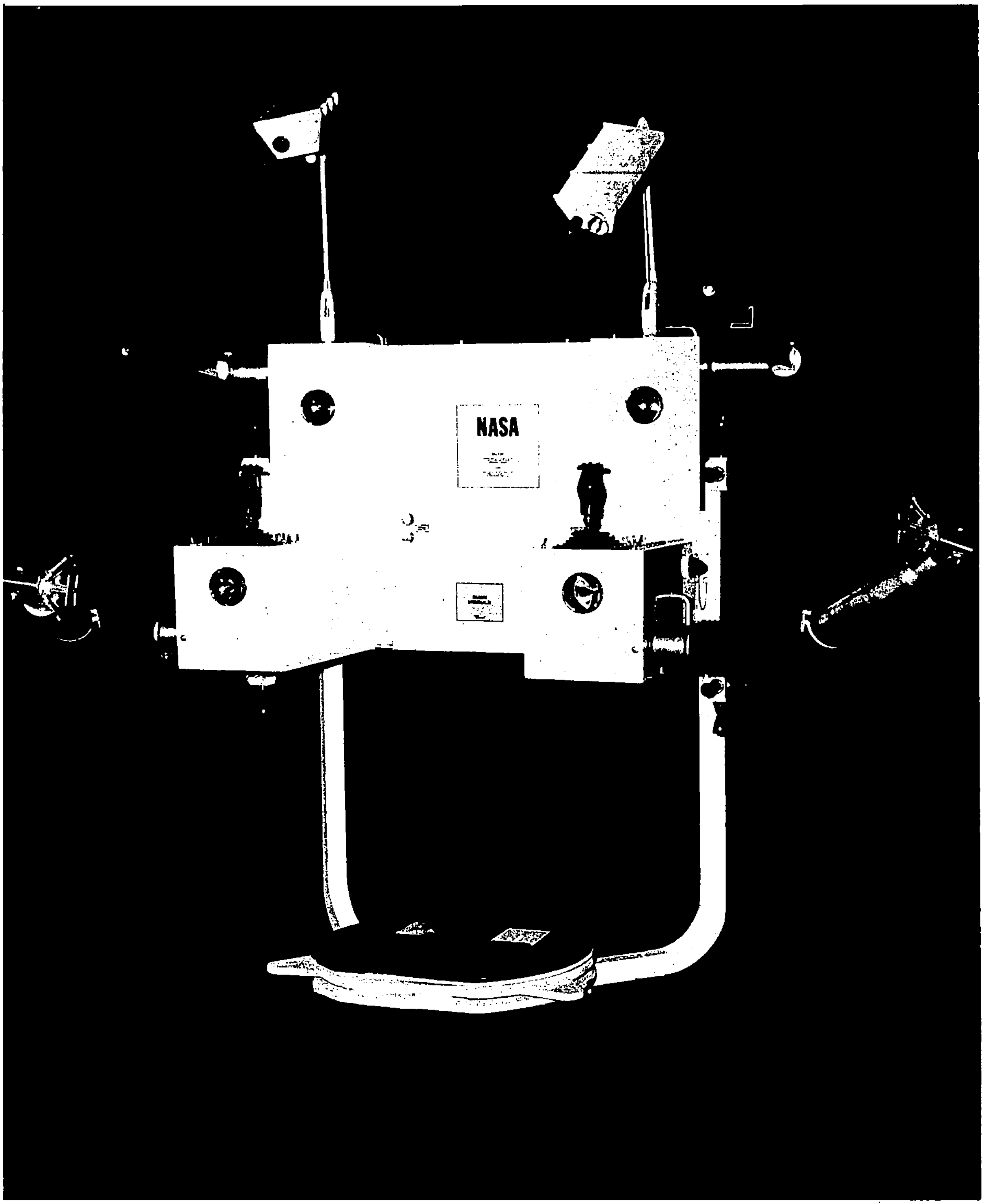


Figure 5. Main Module

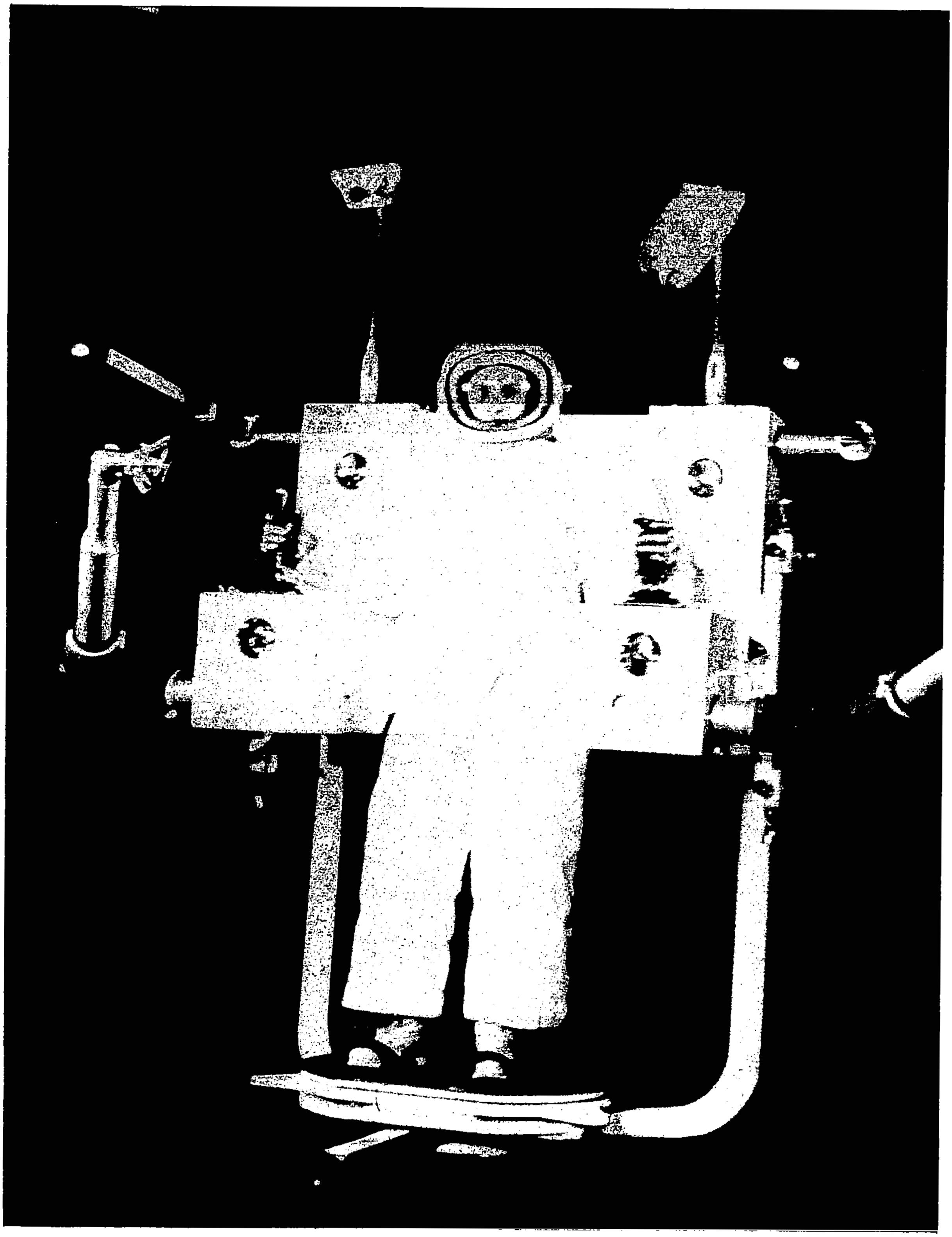


Figure 6. Main Module with Astronaut

Figure 7. Long Range Rendezvous Module Showing Instrument Cluster

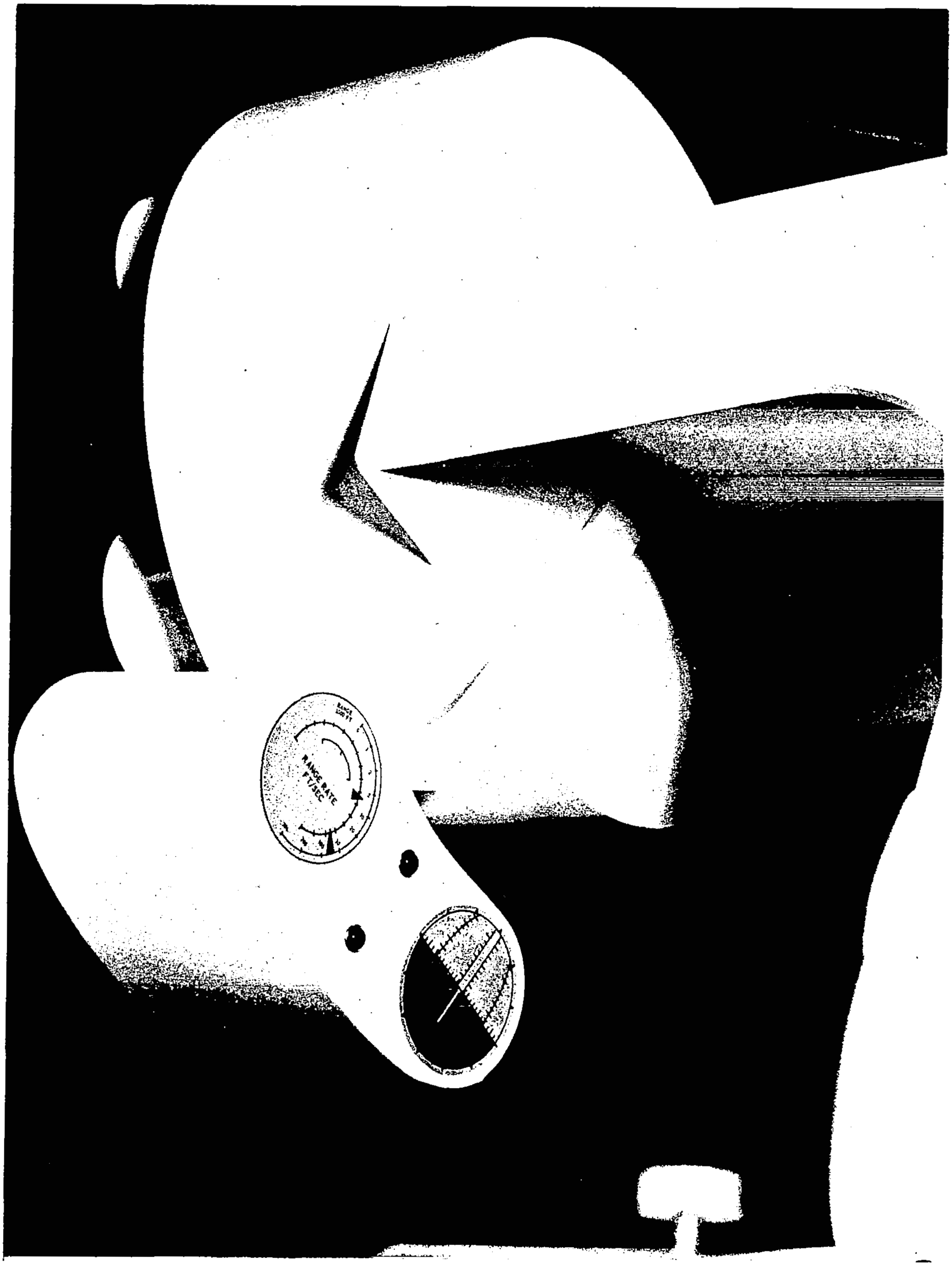


Figure 8. Long Range Rendezvous Module Showing Instrument Cluster

Extended Propulsion Capability Module

The extended propulsion capability module supplements the main module fuel system on missions for which a large fuel demand is anticipated. The module, which was sized for 150 pounds of hydrazine fuel, is composed of two hydrazine cylinders and a nitrogen pressurization system. The pressurization system pressure is slightly higher than that of the main module. The main module fuel tank is therefore full until all fuel is depleted from the auxiliary fuel tanks.

The module is attached to the underside of the main module as shown in Figure 3. Also in the lower right hand corner of Figure 2. Self-sealing quick-disconnect fuel couplings are used.

The extended propulsion capability module increases the ΔV capability of the main module from 298 ft/sec to 1085 ft/sec. The ΔV capability of a full up platform (main module, extended propulsion module, long range rendezvous, payload module) is 975 ft/sec. The ΔV is lower if the platform is used to position massive hardware in orbit. For example, the ΔV capability for a maximum configuration platform plus a 1000 pound payload is $190 \times 32.2 \ln \frac{2354}{2154} = 543$ ft/sec.

Payload Module

The payload module contains the tools, spare parts, rescue gear, repair kits, test equipment, special work aids, and other sundry payloads that may be required during orbital operation of this work platform. The module is mounted through adjustable vertical supports to a bearing plate in the "floor" of the main module. On missions not requiring an extended propulsion module, the payload module is positioned directly below this main module. When the extended propulsion module is used, it is mounted under the main module and the payload module below it as shown on Figure 3. The payload module is open on the top side, exposing the contents to the astronaut. The module may be rotated about its vertical axis to provide better access. Figure 9 shows the platform mockup with the compartment rotated 180 degrees from its normal position.

The zero g environment dictates that the equipment be firmly held in place when not in use to prevent them from drifting about. NASA has developed methods of storing items in zero g. Velcro, a material composed of minute hooks and sockets, is used extensively in the Apollo program and would be considered for use in the payload module. Mechanical retention methods such as spring clips should also be considered.

The tools contained in the payload module would be tailored for specific mission requirements. On a typical maintenance mission the module might contain both battery powered zero reaction tools, and hand tools. Battery powered, zero reaction tools offer several advantages. Powered tools are faster and less fatiguing to use than manual

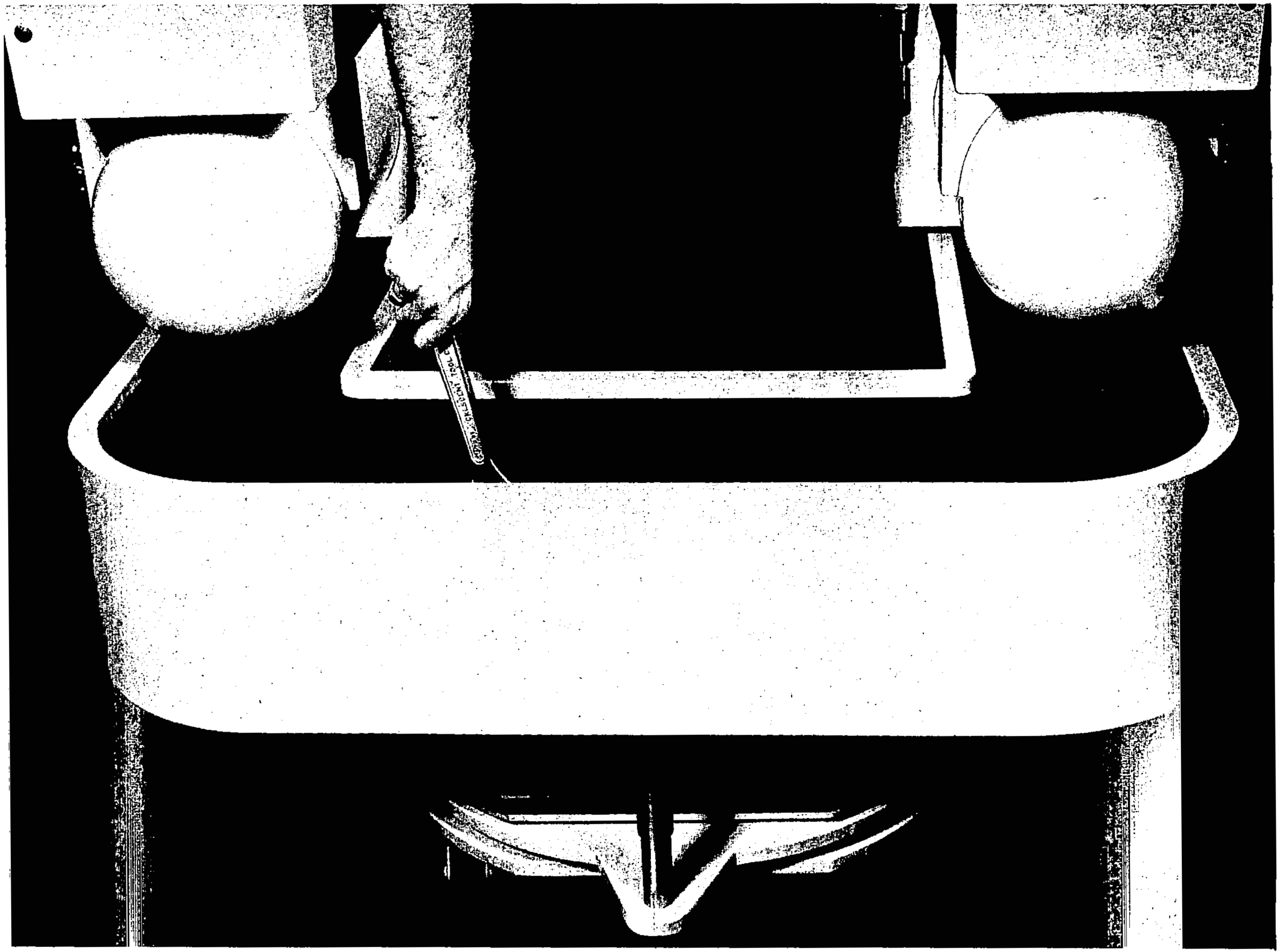


Figure 9. Payload Module

types. The zero or near zero reaction types require a minimum amount of astronaut restraints because the forces transmitted from the work piece to the astronaut and to the work platform are small. The astronaut would therefore be free to assume a wider variety of working positions than he would be able to assume when working with reaction tools.

The Martin Company developed a tool kit for space application (reference 18). The tool kit included:

12 VDC motor	Work light (2)
Impact attachment	Bonding Applicator
Saw attachment	5 Pound Silver Zinc Battery
Drill attachment	Accessories (sockets, saw blades,
Hammer	screwdriver blades,
Screwdriver handle	extension bars,
Restraint buttons	small parts holder)

The complete tool kit weighs 38 pounds. The powered drill, saws, and impact wrench are of the zero reaction type.

Certain tasks may not lend themselves to powered tools. The torquing of large fuel line fittings, for example, may be best accomplished with manually operated wrenches. Some assembly and disassembly operations may require leverage that is best applied through a prying bar.

Any spare parts, repair kits, test equipment, auxiliary lighting, wire, tape, tethers, special manipulator hands, and other special work aids required to perform a mission will be contained in the payload module. Electrical power required by these devices is also contained in the module. Unless the electrical requirements are unusually severe a rechargeable silver zinc battery will be used.

SECTION 4

SUBSYSTEM DETAILS

Propulsion System

The two classes of useful moment producing devices for attitude control are the momentum sink and mass expulsion. For this application, it was judged that mass expulsion best meets the requirements. The most widely used version of mass expulsion for attitude control is the gas jet, and the moment system can be integrated right into the translation system, sharing the same jets. It is expected that the attitude stabilization system impulse requirements will represent on the order of 20% of the total mission impulse. As a result of a literature review on this subject, in conjunction with a configuration evaluation of the proposed vehicle and its performance requirements, an integrated all jet propulsion and stabilization system was selected.

The choice of propellants for the system started with the consideration of four types: cold gas, heated gas, liquid bipropellants and monopropellants, and solid propellants. Published results of similar studies on propellants for various space propulsion systems provided a wealth of data which was used in conducting the tradeoff study. The following requirements were established to evaluate the propellant tradeoff.

- 1000 ft/sec Δ v ($\sim$40,000 lb-sec total impulse)
- High reliability (state-of-the-art and simplicity)
- Good pulse mode performance (both I_{sp} and impulse bit repeatability)
- Storage stability
- Low exhaust plume temperature
- Low toxicity

The 40,000 lb-sec total impulse requirement quickly narrowed the field down to either liquid bipropellants or monopropellants in order to meet reasonable weight and volume requirements. Comparing these two against the remaining more specific requirements led to the selection of monopropellants. The bipropellants (typically N_2O_4 and Aerozine 50) offer higher steady state I_{sp} but have serious shortcomings with regard to exhaust plume temperature, pulse mode performance, and complexity compared to monopropellants like hydrogen peroxide or hydrazine. The high flame temperatures degrade motor life and reliability in addition to increasing the astronaut impingement hazards unless the motor is operated off optimum mixture ratio with significant performance loss. The pulse mode performance is significantly reduced at short pulse widths (see Figure 10) due to mixing losses on startup and dribble losses on shutdown. The system complexity is about double that of a monopropellant, and combustion instability and ignition pressure spikes have been chronic problems with bipropellants. On the basis of these tradeoffs, bipropellants were eliminated from further consideration.

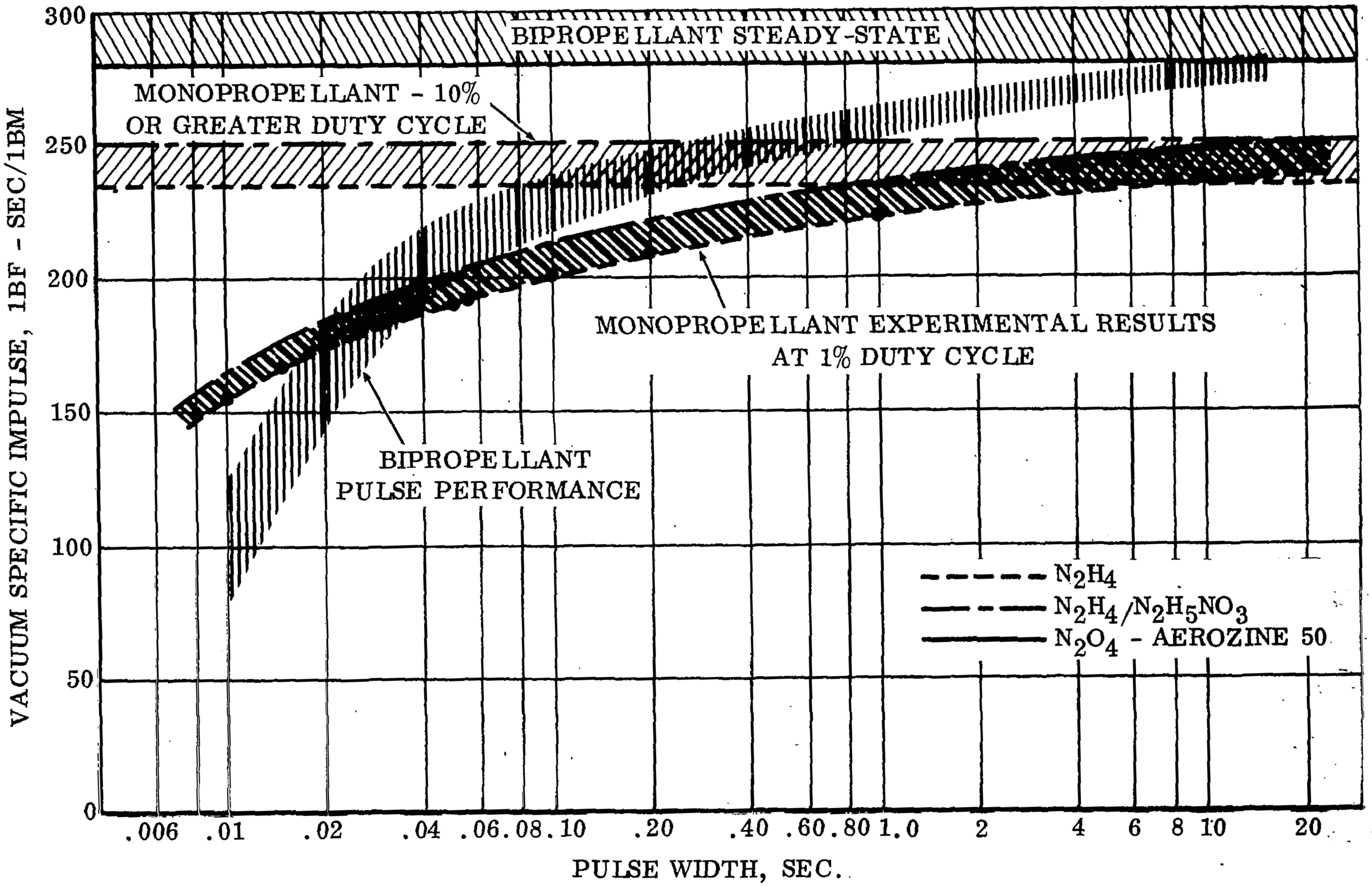


Figure 10. Vacuum Pulse Performance Comparison

The two monopropellants considered were hydrogen peroxide and hydrazine. Hydrazine was the final choice based on higher pulse mode performance and more faborable storage stability. There are large delivered specific impulse gains for hydrazine based systems over a hydrogen peroxide system at the high expansion ratios ($\sim$50:1) desired in this space application. The hydrogen peroxide system suffers condensation losses at expansion ratios above approximately 15:1. The improved storage stability of hydrazine compared to hydrogen peroxide is well documented. Hydrazine does have a higher plume temperature (1800 vs. 1300^{o}F) but this is not a significant problem. If necessary, the exhaust temperature can readily be lowered by using a hydrazine/water mix. Use of diluted hydrazine offers another advantage in that the freezing point can be lowered considerably (see Figure 11). The design flexibility of a hydrazine based system is of itself a large plus factor leading to its selection.

The state-of-the-art of hydrazine propulsion technology has advanced considerably in the last few years. The most notable advancement being the development of a new spontaneous catalyst, Shell 405, by the Shell Development Company. This catalyst has been shown to be a true breakthrough in hydrazine propulsion technology. Prior to Shell 405, the use of hydrazine as a monopropellant was limited (Ranger, Mariner) due to the requirement for an auxiliary starting system such as a hypergolic start slug, electrical heating, etc. With the new spontaneous catalyst, many new propulsive applications can be considered, especially those requiring multiple start or pulse mode operation. It is expected that many future systems will utilize this monopropellant as evidenced by the development program recently undertaken by Rocket Research Corporation to develop a hydrazine attitude control system for an Air Force surveillance and reconnaissance satellite. This system will be designed to performance and environmental requirements very similar to those of an EVA work platform application.

For this project a 16 thruster configuration was rather arbitrarily chosen, as was the firing configuration. All 16 thrusters are identical. The thruster firing configuration consists of four thrusters for fore or aft translation; two thrusters for lateral or up and down translation; and four thrusters for attitude stabilization moments about any of the three principal axes. All stabilization moments are applied as couples. The detailed study required to optimize these choices was beyond the scope of the project, but a brief look at the assumed configuration was taken to confirm that it was reasonable, and to obtain a feel for the design flexibility available to meet specific requirements as yet undefined.

In other EVA studies it has been indicated that typical closing velocities will be 15-20 ft/sec for rendezvous maneuvers at ranges from 1000 to 7000 feet. It has also been indicated that a minimum acceleration capability of .5 ft/sec^2 is required to safely approach targets of approximately 10 foot diameter at closing velocities of this magnitude. For a design vehicle weight of 1554 pounds (main module, astronaut + PLSS, extended propulsion module, long range rendezvous module, payload module with tools, and a 200 pound "payload"), the required thruster size to achieve a minimum fore and aft translational

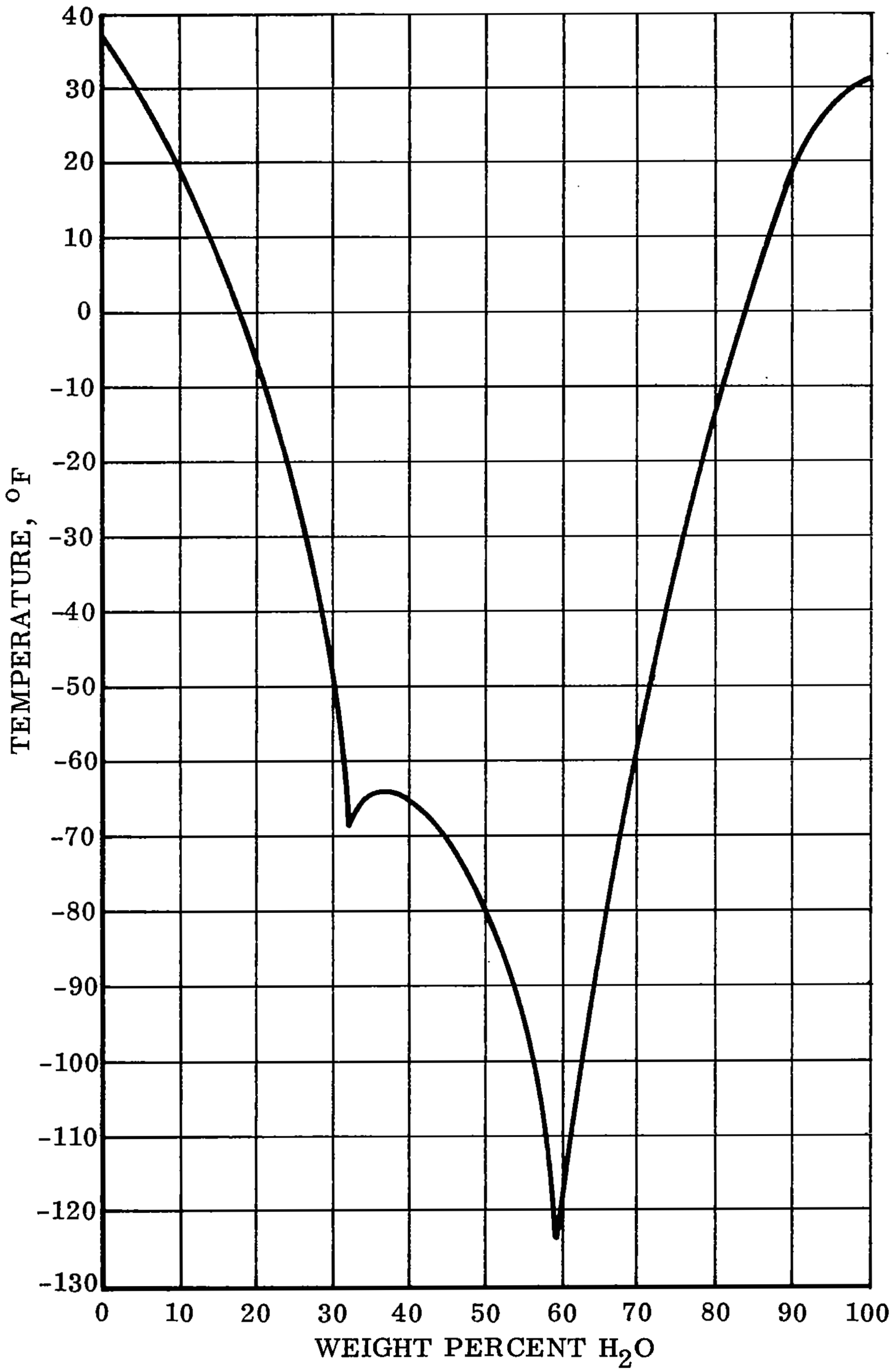


Figure 11. Freezing Point N_2H_4-H_2O Solutions

acceleration of .5 ft/sec^2 is $T = \frac{1554}{32.2} (.5) \frac{1}{4} = 6.03$ pound each. Since there are only two vertical thrusters, the lateral and up and down acceleration capability is only .25 ft/sec^2.

The stabilization moments available about each axis are 2Td where d is the moment arm between the thrusters that form the various moment couples. For the described configuration the moment arms are 22 inches for pitch and 50 inches for yaw. The roll moment is made up of two couples with one of each of the above moment arms giving an effective $d = \frac{50 + 22}{2} = 36$ inches. The resulting control moments are 21.6 ft-lb in pitch, 49 ft-lbs in yaw, and 35.4 ft-lbs in roll.

The estimated moments of inertia for the maximum vehicle configuration are 50, 56, and 100 lb-ft sec^2 in pitch, yaw, and roll respectively. The resulting angular acceleration capabilities are .43, .87, and .35 RAD/sec^2 respectively. When the vehicle configuration is limited to the basic module, the moments of inertia are reduced to about 26, 44, and 63 lb-ft sec^2 in pitch, yaw, and roll, respectively. The resulting angular acceleration capabilities are then increased to .87, 1.1, and .56 RAD/sec^2 respectively. The accelerations are similar to values encountered in other studies and were therefore assumed to be compatible with typical stabilization system requirements.

Based on these considerations, the propulsion system incorporated into the work platform employs thrusters sized to be representative of 5-10 pound thrust units. The basic module fuel tank is sized for 50 pounds of hydrazine. The extended propulsion module is sized for an additional 150 pounds.

The delivered specific impulse is very much a function of duty cycle and pulse width. Based on the data of Figure 10 an overall delivered specific impulse of at least 190 sec seems reasonable. This value provides the basic module alone a

$$\Delta V = I_{sp}\, g \ln \frac{W_o}{W_e} = 190\ (32.2) \ln \left(\frac{1052}{1002}\right) = 298 \text{ ft/sec.}$$

where W_o = initial weight

W_e = final weight

Propulsion capabilities for various work platform module combinations are given in Table 1.

The characteristics of an existing thruster made by Rocket Research Corp. are given in Table 2. A 5-10 pound thrust unit would be physically a little bit larger but the pulse performance, response time, etc., would be very close to the values given.

TABLE 1. PROPULSION CAPABILITY

Configuration	Main Module With Astronaut	Extended Propulsion Capability Module	Payload Module With Martin Tool Kit Only	Long Range Rendezvous Module	200 Pound Payload	1000 Pound Payload	W_o #'s	W_e #'s	ΔV Capability Ft/Sec
1	X						1052	1002	298
2	X		X				1102	1052	284
3	X			X			1125	1075	278
4	X		X	X			1175	1125	266
5	X		X	X	X		1375	1325	224
6	X		X	X		X	2175	2125	142
7	X	X					1231	1031	1085
8	X	X	X				1281	1081	1035
9	X	X		X			1304	1104	1020
10	X	X	X	X			1354	1154	975
11	X	X	X	X	X		1554	1354	842
12	X	X	X	X		X	2354	2154	543

TABLE 2. ROCKET THRUSTER CHARACTERISTICS

Engine ID - RRC-TA-1.5-002

Thrust (Vacuum) - 2 lbf

Expansion ratio - 50:1

Throttle range - Pulse mode

Chamber pressure - 150 psia

Propellants - hydrazine MIL-P-265363

Delivered specific impulse (steady state) - 222 lbf-sec/lbm

Delivered Specific Impulse (min. pulse width) - 115 lbf-sec/lbm @ duty cycle 1%

Minimum delivered impulse bit (lb-sec) - 0.01 lbf-sec

Total Impulse Repeatability (lb-sec)

(1)	For one engine:	@ min. pulse width - ± 5%
		@ 100 ms pulse width - ± 1%
		1st pulse vs. 20th pulse - ± 1% hot bed
(2)	Engine to engine:	@ min. pulse width - ± 7%
		@ 100 ms pulse width - ± 5%

Response time: On signal to 90% F 0.013, off signal to 10% F 0.042 sec, hot bed conditions

Thrust chamber materials - 321 stainless steel

Nozzle materials - 321 stainless steel

Throat material - 321 stainless steel

Thrust chamber and nozzle length - 3.50", diameter; 0.933"

Thrust chamber and nozzle weight - 0.16 lbm

Injector weight - 0.10 lbm; Catalyst weight - 0.04 lbm

Propellant valve weight - 0.20 lbm

Total engine weight - 0.50 lbm

Propellant valve response (ms): open - 6; close 6

Valve power required (watts) - 2

The propulsion system employs regulated nitrogen with a 3000 psi supply for fuel expulsion. This choice was made without the detailed tradeoff study which would be necessary for final design selection. The choice was made because it is a method well within the state-of-the-art and has inherent reliability through simplicity. However, it is recognized that this choice does carry a rather important drawback, when all mission requirements including servicing, are considered. That is, that it requires a high pressure recharging system in the mother ship which would be heavy and relatively complex. In addition, its weight and volume characteristics are less than outstanding. A bootstrap hydrazine gas generator would give improvements in all three areas at the expense of simplicity. Recent work on these units indicates that they are state-of-the-art and current reliability data may make this system a better choice overall. Servicing requirements could then be made identical to those of refueling the propulsion system fuel tanks at a considerable overall savings compared to the nitrogen system.

The center of gravity of the vehicle will move appreciably on the vertical axis as various modules are added to the basic module. The estimated travel is about 5 inches in going from the basic unit to the maximum module configuration. Relatively minor center of gravity changes will occur in the other two directions. By making the thruster mounting arms adjustable in the vertical plane, the large center of gravity change is readily accommodated (see Figure 12). The concept covers either an infinitely variable movement or a number of discrete positions associated with various vehicle configurations. The completely variable approach would allow considerably more flexibility, especially with regard to variable payloads and fuel consumption corrections.

There are many possible alternative moment arms, firing configurations, and/or mixtures of thruster sizes, which might be used to obtain the desired high fore and aft acceleration capability, while still maintaining attitude control acceleration rates which are compatible with typical stabilization control system requirements. The system described here is a simplified "first look" at a feasible selection. Detailed design as to optimum combinations is left to future study as requirements become more definitive.

Stability and Control

A rather extensive amount of work has been performed in recent years regarding maneuvering techniques related to extravehicular activity. Various research and development programs have been conducted which involved theoretical analysis, computer simulations, air-bearing simulations, etc. In this manner the performance capabilities of numerous concepts have been evaluated. The concensus of these studies is than an automatic attitude stabilization system is necessary to accomplish the type of EVA missions anticipated for this vehicle concept.

The most fundamental concern with regard to any unstabilized vehicle is tumble recovery in six degrees of freedom. Serious doubt exists regarding an astronaut's ability to manually recover in such a situation. Until such time as this question is resolved, it

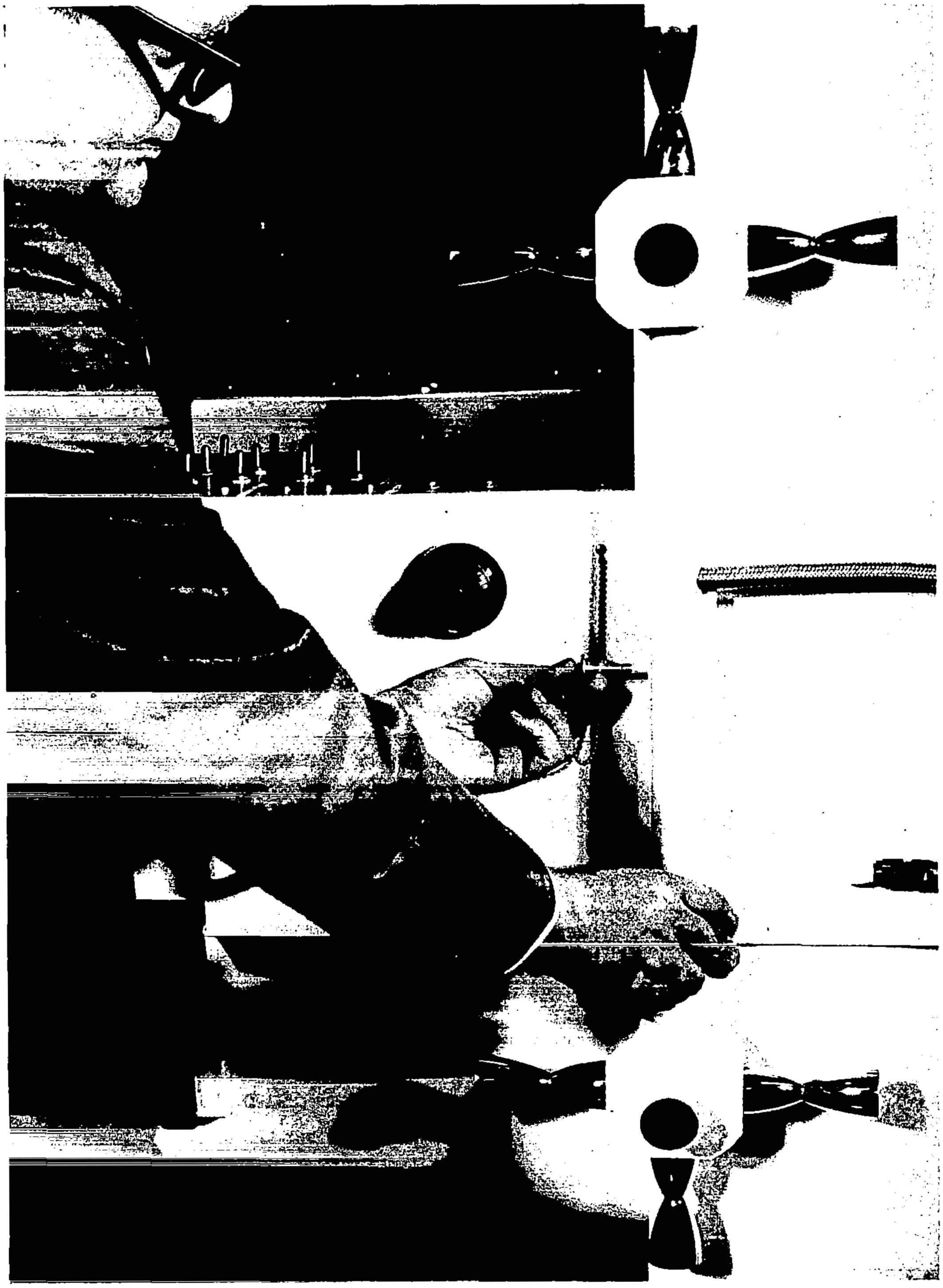


Figure 12. Thruster Positioning Adjustments

can only be assumed that a stabilized vehicle is mandatory for the type of missions anticipated herein.

The large amount of work done by LTV on a stabilized back pack is the basis of the type of stabilization system described herein. The system's control electronics and rate gyros provide automatic "hands-off" attitude hold. Both translation and rotational maneuvers are accomplished only by manual command. All attitude corrections are limited to a fixed rotation rate and rotation stops automatically when the command is released. It has been shown that a moderate range of control parameters exists for which superior performance is obtained.

The attitude control system has two modes of operation. In the automatic mode the vehicle attitude is automatically stabilized. A manual rotation command will then result in acceleration to a constant predetermined rotation rate which is then maintained until the command is removed. Removing the command automatically provides angular deceleration to stop the rotation and the new attitude is then automatically stabilized. Translation commands produce continuous linear acceleration (interrupted for automatic attitude stabilization corrections) until the command is removed. Deceleration must then be manually commanded.

The second mode of operation is the manual or unstabilized mode wherein attitude corrections must be made manually. A rotation command then produces continuous angular acceleration and the rotation must be stopped manually by commanding rotation in the opposite direction. Translations are the same as in the automatic mode except that there are no automatic attitude corrections made to maintain a stabilized attitude.

All manual commands originate at the control sticks mounted on the "ARMS" of the main module at a convenient location for the astronaut. Attitude commands are made with the right hand controller and translation by the left. No two commands can be given simultaneously by the control sticks and if both controls are applied, precedence is always given to attitude commands. Both controls are spring loaded OFF and are not proportional, they are either ON or OFF.

Linear pulse ratio modulation determines the length and frequency of most thruster firing. The details of this subject are complex and beyond the scope of this project. It sufficies to show that good pulse mode performance of the propulsion system is mandatory as dictated by the stabilization system's mode of operation. In brief, a certain error level is established above which thruster firing is continuous while below this level thruster firing becomes intermittent with thruster pulses becoming shorter and further apart as the error decreases. Below a given level the thrusters are off continuously. This results in an average angular acceleration which is proportional to the error.

The estimated weight and volume of the stabilization and control system is based on published figures for the LTV back pack design.

Communications

This is an area where not much development will be required and where the anticipated requirements can be met in a relatively low volume, low weight package. The detail communication system requirements have little effect on the conceptual design of the vehicle and therefore were not pursued beyond the point of a very general discussion of the matter and the acceptance of a preliminary weight estimate of 15 pounds to be allowed for in the basic module.

Current Portable Life Support System (PLSS) design includes primary and backup duplex voice transmission and reception, as well as seven channels of telemetry. Six channels are used for suit operational and environmental data, oxygen pressure, water supply, suit pressure, suit oxygen inlet temperature, suit water temperature, and battery current. The seventh channel carries on electrocardiogram signature. Its range is limited and it seems likely that a transceiver would be required as a relay between the astronaut and the mother ship whenever he leaves the EVA vehicle while at a remote worksite. Even while in the vehicle at long range from the mother ship, a system to boost the range of the PLSS unit seems likely. APL's preliminary estimate of 15 pounds and a corresponding packaging volume were allowed for in the basic module conceptual design.

Two television units were also provided to give complete coverage of the astronaut's movements as well as detailed coverage of the work he is performing. The mockup of these cameras was based on a current Westinghouse design which have a weight of about seven pounds each.

Illumination

Artificial illumination is essential for most EVA tasks. A literature search was made in an attempt to determine in general what the requirements might be.

The Martin Company studied the location and intensity of light sources required for visual recognition of significant features. Results of their study indicates that whether or not the maintenance worker will require artificial lighting to illuminate his work area depends not only on the illuminance of natural light sources such as the sun, but also the shadows cast across the work area by himself and other objects. (Reference 18.) Because there is no atmosphere to scatter and diffuse incident light, shadows will be very prominent and of high contrast. If it is desirable for the worker to perform in the shadown areas and through access opening in maintenance compartments, it will be necessary to use artificial lights or have reflectors at appropriate locations to adequately illuminate his work.

Intensity of the work light is significant because it directly influences the size of battery needed to power the light source. Martin studies indicate that the worst condition occurs where the astronaut must look beyond a glaring spacecraft skin into an access opening. In tests simulating this condition, 40 foot candles of light were required to provide sufficient illumination. The tests, however, did not take into account the effect of the filter in the astronaut's helmet.

Another conclusion reached by Martin from their study was that the optimum configuration for a general illumination system consists of two light sources, one on either side of the astronaut located at eye level. The system should evenly illuminate a minimum of 30 degrees of the operator's central vision field.

Pairs of general illumination lights are provided on the work platform at shoulder and waist level. As conceived, the lower pair would have a rather broad beam and would be used for general illumination. The upper pair would incorporate a narrow beam that can be directed at the object being worked upon. Lights are also mounted with each television camera. Position of the T.V. and light assembly can be controlled remotely by the personnel aboard the mother ship or directly by the astronaut. Supplemental lights, reflectors and shades can be included in the payload module as required.

The main module also is equipped with navigational lights to aid the astronaut's associate in visually tracking the space platform. A total of 136 watt-hours of power has been allotted for illuminator devices aboard the main module.

Manipulators

The work platform incorporates two bilateral (master-slave) manipulators. They were included in the main module because, in our opinion, they would be useful in the vast majority of missions. Bilateral manipulators could serve the astronaut in several ways. First, forces applied by the astronaut are magnified by the manipulators. Second, forces can be "locked," relieving the astronaut from applying the force and freeing his hands for other uses. Third, manipulators will extend the astronaut's reach. He can reach things with the manipulators which he could not otherwise do except by leaving the platform or moving the platform to a new location. Fourth, in using the manipulators the astronaut is protected from possible harm from handling directly hot or sharp objects that could damage his space suit.

However, the use of manipulators in space remains to be proven and much development work needs to be done to provide a light weight system suitable for space applications. Also, it should be noted that presently the range of manipulator capabilities is only a few percent of the human hand. Simple tasks may require 6 to 10 times as much time to perform as would be needed if the task were performed directly with the bare hand. Development work is not likely to improve this deficiency appreciably. If it becomes apparent from further studies or from manipulator development programs that the manipulators cannot be used to advantage on a large percent of the missions, consideration should be given to packaging the manipulators as a separate module. They would then be taken on only those missions where they could be used effectively. Since the manipulator weight is estimated to be 46 percent of the total main module weight, a savings in fuel expended of 46 percent could be anticipated on missions not using the manipulators.

A number of different manipulators have been developed and put into use. All of these have been designed for ground applications. Most are used in nuclear (hot cells) laboratories or other shielded facilities. Manipulators can be grouped into two basic type--unilateral and bilateral.

A unilateral manipulator consists of a mechanical working arm having seven or more independent, motor driven motions which are controlled in speed and direction by proportional controllers. This type of manipulator is termed unilateral because there is no force or position feedback between the working arm and the controls.

A bilateral manipulator is comprised of a master (or control) arm and a slave (or working) arm. Bilateral manipulators have at least seven independent motions. Motions and forces produced at the master arm by the operator are transmitted to the slave arm and, conversely, motions and forces acting upon the slave arm are transmitted to the master arm. Because of this force and position feedback, the manipulator is termed bilateral.

Of the two basic manipulator types, bilateral manipulators show the most promise for a space application. Unilateral manipulators are too slow in performing work, lack ability to accommodate to restrained paths, and could easily damage other equipment because of the lack of force feedback. Bilateral manipulators provide a natural mode of operation, good sensitivity and good efficiency in performing work. With these manipulators, an operator is able to feel (through his hand and arm muscles) the forces involved in the manipulations being performed. Operation of the manipulator is simple and natural. The operator merely moves the master handle as he wants the slave "hand" to move. A 1:1 motion correspondence exists between the motion of the master handle and the motion of the slave hand. Master-slave manipulators are completely reversible. Because of this, an operator can follow a complex path using master-slave manipulators in much the same way as he would follow the path if working directly.

The Argonne National Laboratory, a leader in the development of manipulators for "hot" laboratories, has investigated the use of manipulator systems for space applications. The manipulator system recommended for the EVA platform is based primarily on a study which they performed for NASA's Marshall Space Flight Center during 1966 and 1967. (Reference 13).

Design objectives of manipulators for use on the space platform are that they be:

- Versatile
- Simple to use

- Lightweight
- Use a minimum amount of energy (both man's and other energy sources such as batteries)
- Be capable of working throughout a large volume
- Should be configured such as to restrict the astronaut's view as little as possible.

The manipulators should be capable of doing a wide variety of tasks with minimum amount of change to the manipulator. The slave "hands" should be capable of grasping a wide range of sizes and shapes of objects. It should be possible to use tools efficiently either by having them fit the "hand" or by removing the "hand" entirely and connecting to tools to the wrist stub.

The manipulators should be easy to use and feel natural to the astronaut. Force feedback is a must. Motions of the "slave" should be in phase with the master, i.e., a horizontal move of the master produces a horizontal move by the slave.

Because of the high cost per pound of placing a system in space, the weight must be a minimum commensurate with high reliability.

Power assist, or force, boost between master and slave is desirable. Operators could handle greater loads with power assist and moderate loads could be handled with less fatigue.

The power requirements should be low for obvious reasons of battery size and weight.

Both mechanical and electrical means of connecting the master to the slave were considered. An electrical system offers the following advantages:

- A force boost can be provided so that the force applied by the slave is some multiple of that of the master.
- Working volume is grossly larger than that of a mechanical system.
- Packaging arrangement is more flexible.
- An electrical system is more versatile. For example, it could be modified for remote operation from a mother ship or from earth.

An electrical system has two disadvantages, however. It is heavier than the mechanical system and it requires a cooling system which the mechanical system does not. Weights of two systems analyzed by Argonne were as follows:

> A pair of electrically connected manipulators having a slave working volume of 1100 cubic feet weighed 485 pounds, excluding the power source and cooling system. A mechanical system having a working volume of 145 cubic feet weighed 160 pounds. For the comparison Argonne assumed the force capacity of electrical system to be 50 pounds and the mechanical system 25 pounds.

Further tradeoff studies are necessary to determine an optimum manipulator configuration for the modular work platform. For the present, an electrically driven manipulator was selected. The system was sized for 12.5 pounds at the master and 25 pounds at the slave arm. The working volume at each master control is limited to one cubic foot. The total working volume at each slave approximates a sphere having a 5 foot radius (525 ft^3). To achieve a large working volume at the slave from a small operating volume at the master, it will be necessary to index the controls when the extremes of the operating envelope is reached. Indexing motions allow the slave arm to be repositioned relative to the master arm. A concept of a master control handle is shown on Figure 13. An index switch is provided to reposition the slave arm relative to the master control handle. If, for example, the master handle is moved to the extreme left position, the slave arm will index left when the switch is activated. The indexing motion continues until the switch is released or until the slave arm is driven to its envelope limit. During this operation the manipulator has no force feedback. A second index switch is provided which allows the master handle to be repositioned relative to the slave. When this switch is activated, the slave is arm locked in position and the operator can move the control handle to a more advantageous operating position without disturbing the slave. The slave hand squeeze motion is controlled by the index finger. The squeeze motion control has force and position feedback. This control can also be used as a power

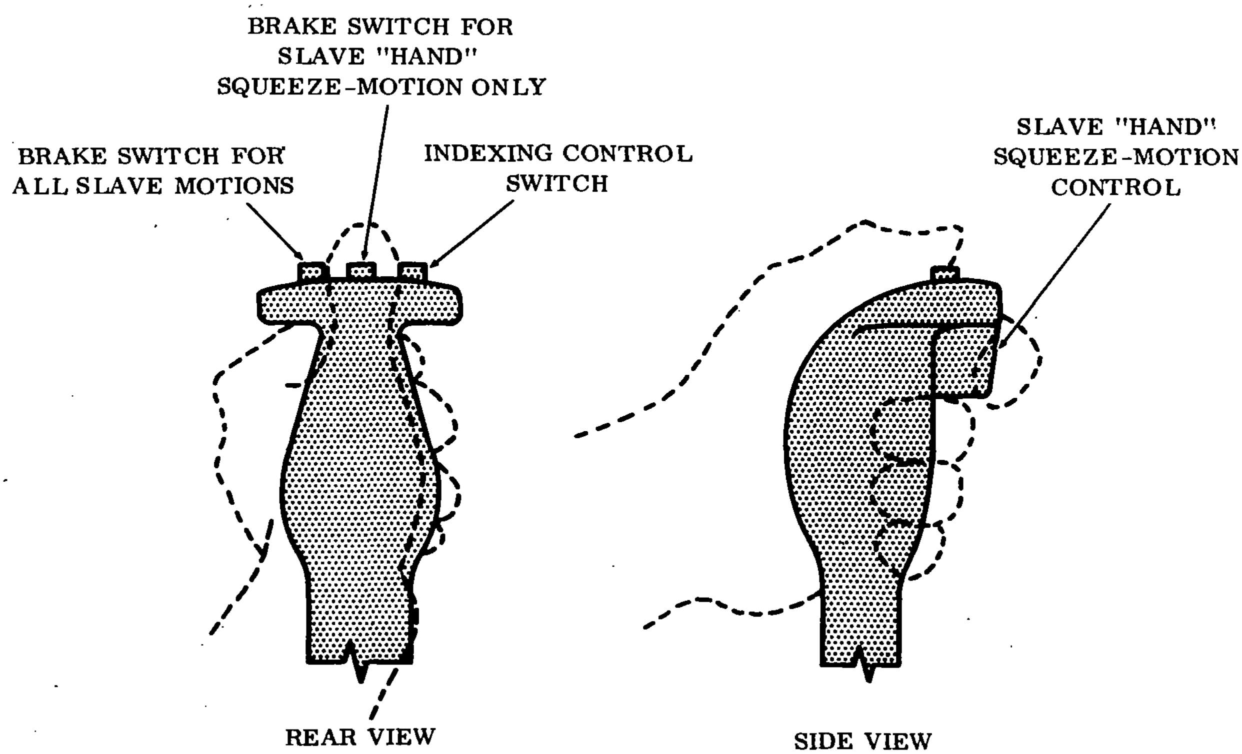


Figure 13. Master Handle Concept

control when the slave "hand" is removed from the slave and tools are attached to the stub wrist. A third switch for the slave "hand" squeeze motion brake permits the operator to hold items firmly without maintaining a squeeze force on the index finger control.

The manipulator controls are integrated with the propulsion controls. A switch located on the control panel near the handle is used to select the function controlled by the handle. Figures 14 thru 16 depicts an astronaut controlling the manipulators.

Worksite Anchors

The anticipated docking procedure for the vehicle is to establish a preliminary docking by means of the manipulators. It is assumed that some edge and/or perturbance is available to accomplish this. Once a grip with one or both of the manipulators is established (preferably with both) a means for reacting minor forces is available for the application of final docking attachments. A three point attachment was chosen to provide complete six degree stability. Considerable docking flexibility is provided by making the two upper worksite anchors rotate in the vertical plane and the lower anchor in the horizontal plane, while all three are telescoping for length variation. A ball and socket type joint is used between the arms and the anchor pads so that the pads are self-aligning when pushed against any surface not normal to the axis of the arm.

In line with providing maximum docking flexibility, the anchor pads chosen are of the adhesive type. A survey of the literature on this subject indicated that promising development work has already been completed. Most of the problems encountered were related to the application of pressure during a short curing period which does not apply in this application. The minor application forces required are readily reacted through the preliminary grasp of the manipulators and curing time is therefore not critical as would be the case without preliminary docking. Electrically heated epoxy adhesive anchor pads were therefore selected.

The undocking procedure leaves the adhesive anchor pad behind by uncoupling the pad to anchor arm joint. Resupply of anchor pads could conceivably be by an automatic dispenser or manually by the astronaut from a supply bin.

Photographs of the EVA work platform mockup in a docking position is shown in figures 17 and 18.

Human Factors

The apparent weightless condition created in near earth orbit will necessitate special accessory equipment for the worker. Although zero reaction tools are expected to be used extensively there undoubtedly will be periods when the astronaut will use conventional

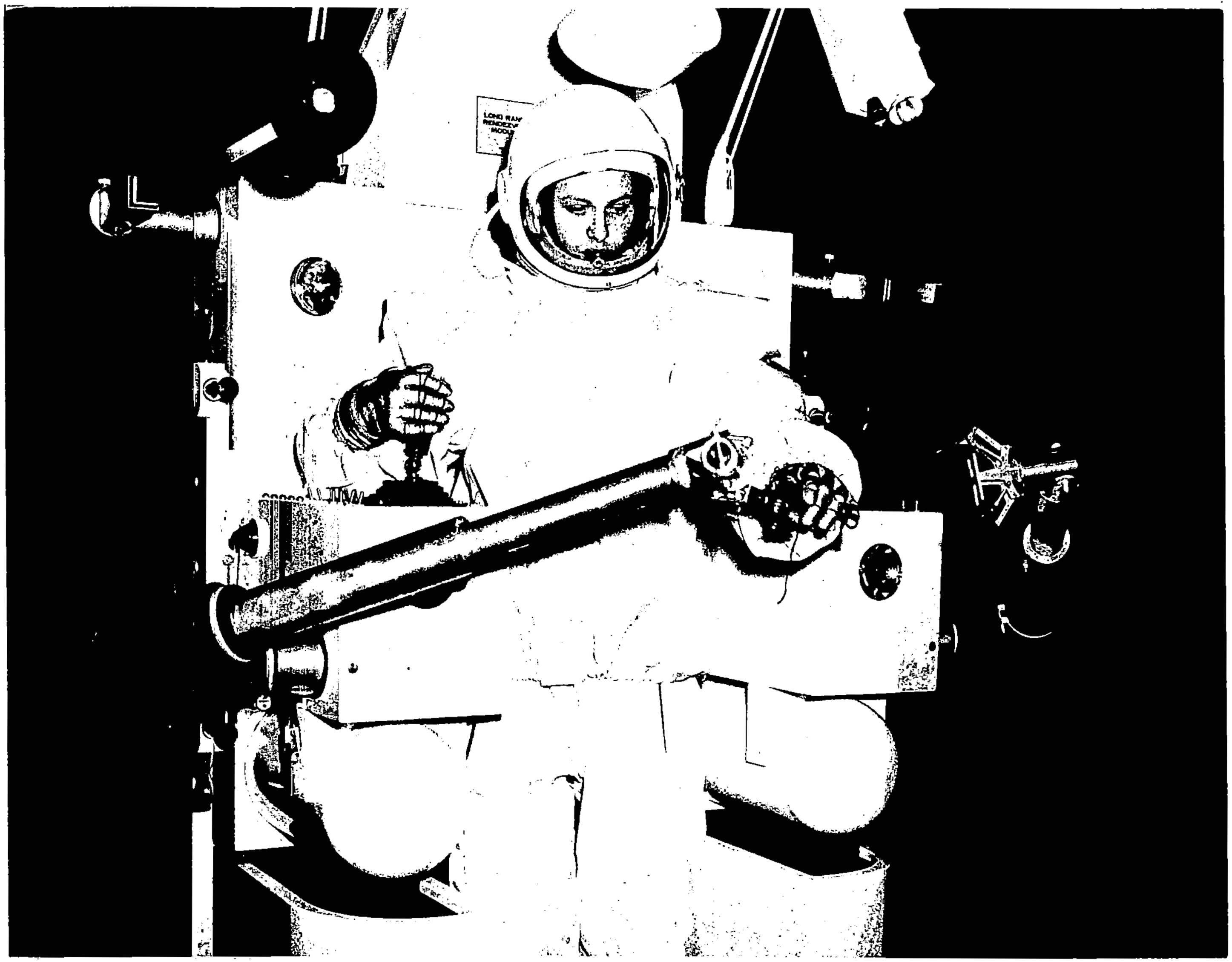


Figure 14. Astronaut Controlling Manipulators

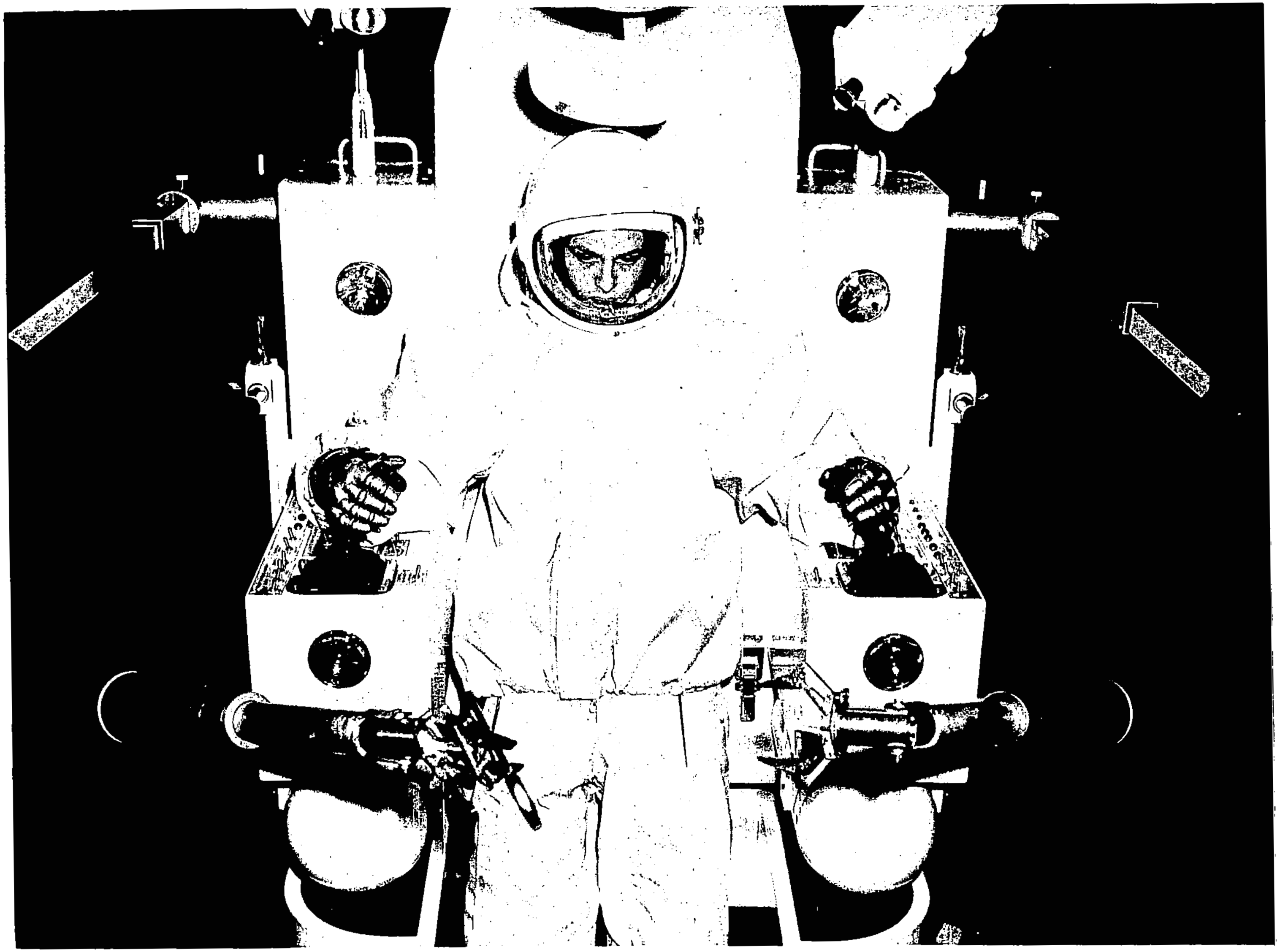


Figure 15. Astronaut Controlling Manipulators

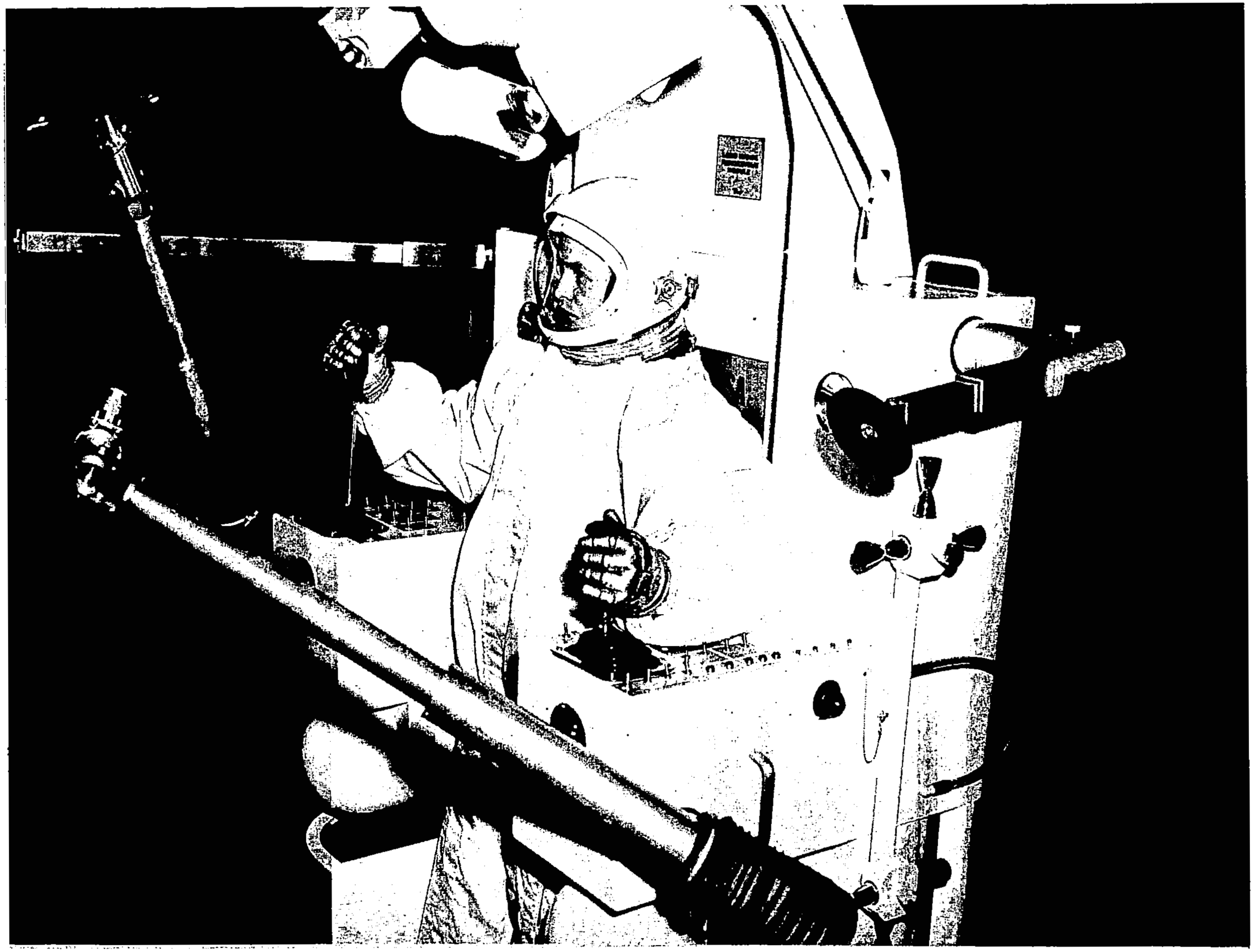


Figure 16. Astronaut Controlling Manipulators

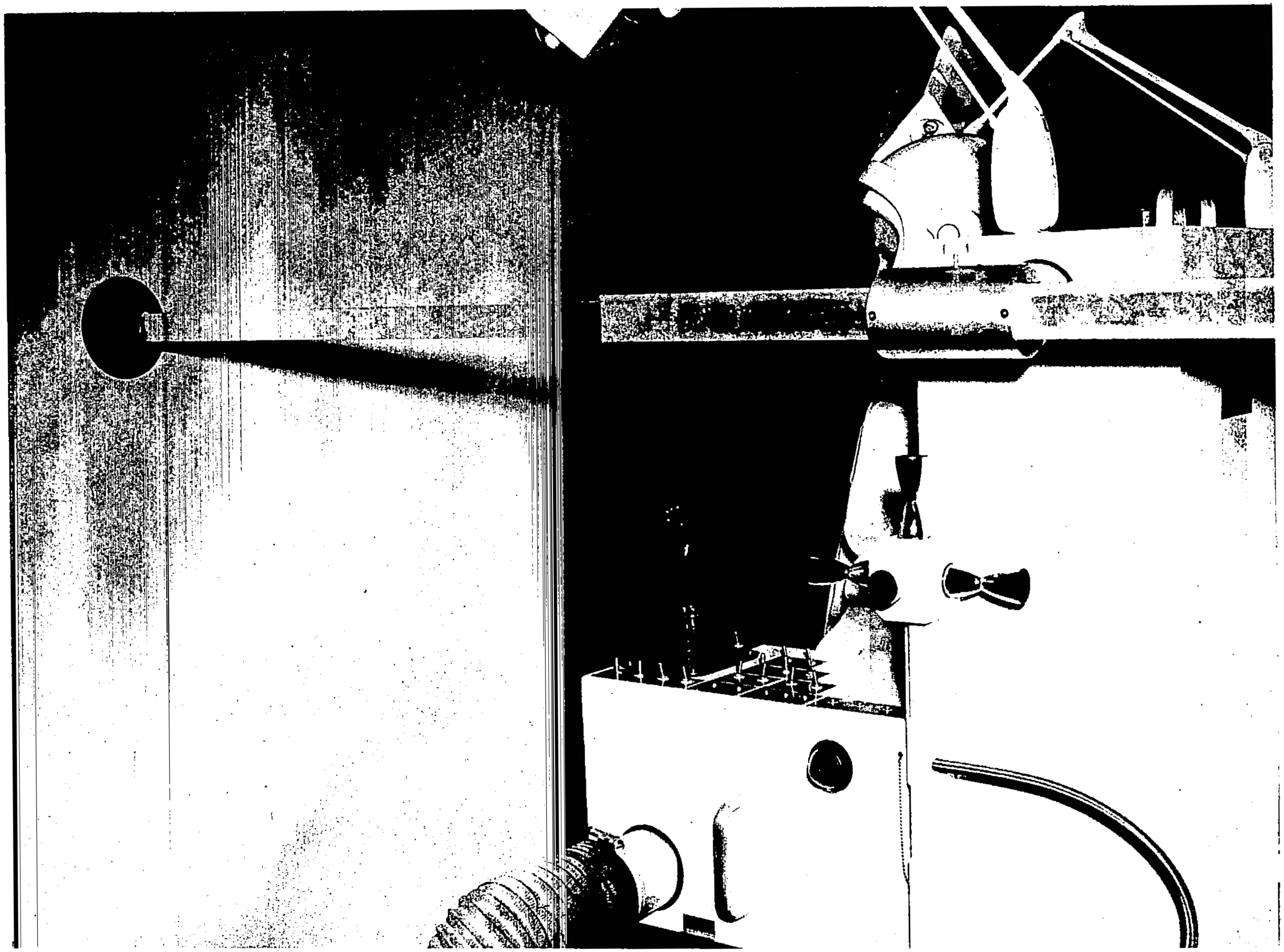


Figure 17. EVA Work Platform in Docking Position

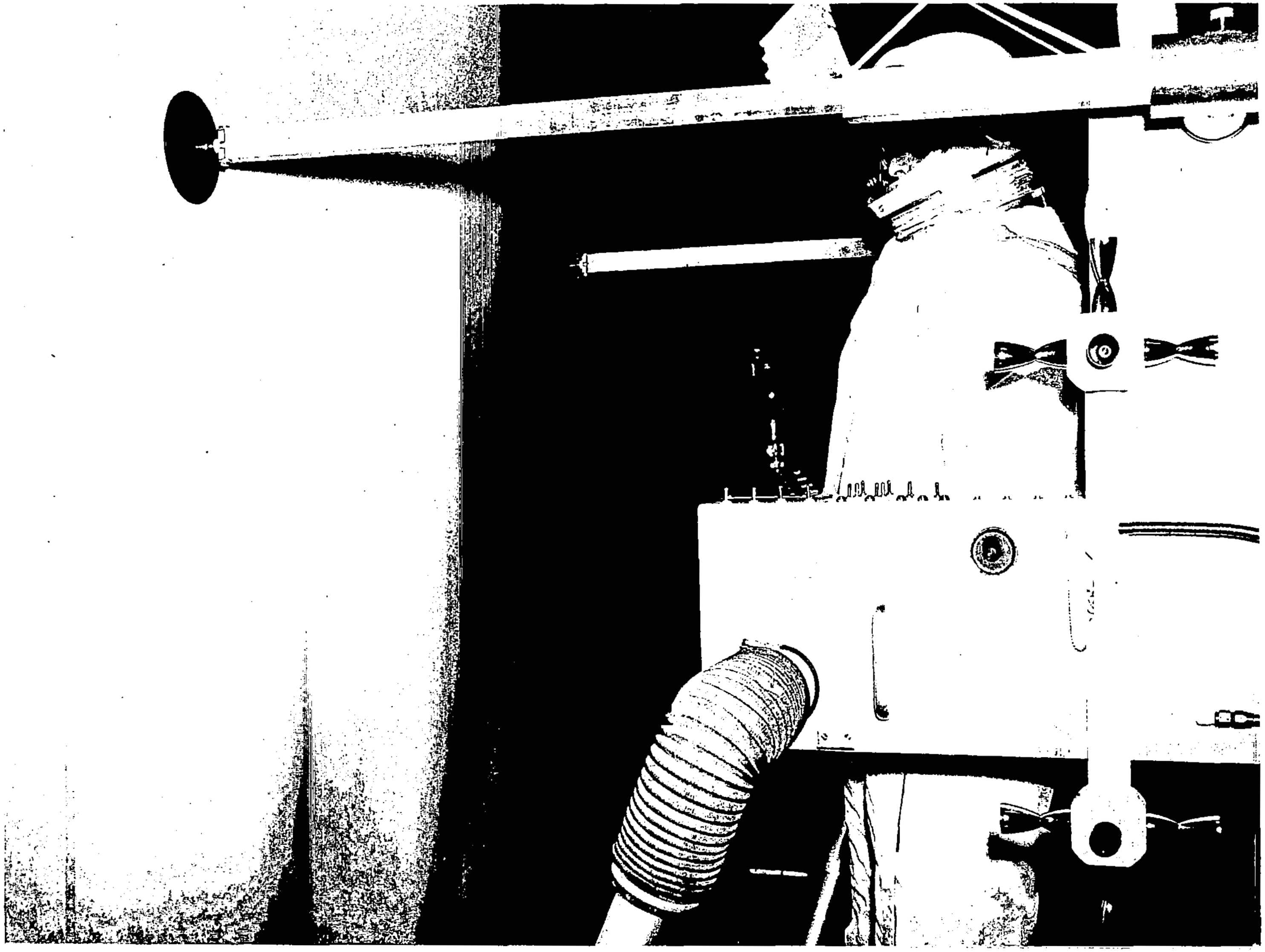


Figure 18. EVA Work Platform in Docking Position

tools and handle components directly. During these periods he will be exerting forces and developing reactions. The platform will be secured to the work site with the three docking arms described previously. An effective means of securing the astronaut to the platform is necessary in order to transmit these reactive forces to it.

Basic considerations for the restraint system envisioned were:

- Restraint attachment/detachment must be quick and easy
- Adjustment of position shall require little time or effort
- Restraint system strength must be sufficient to withstand expected reaction forces
- Location of restraints must allow the astronaut to assume positions best suited for various tasks

Foot restraints were deemed desirable and are attached to a base that is structurally a part of the main module. Individual foot adjustment permits the astronaut to seek a comfortable and efficient working position. A waist restraint similar to the type worn by high window washers was envisioned. Several points of attachment would be available on the platform so that the astronaut could vary his fore and aft position. Length of the belt would also be adjustable. Using these types of waist and foot restraints the astronaut could transmit forces into the platform structure.

The design of the modules must allow the platform to be assembled by a suited astronaut. The fastening devices must be large so that the astronaut can manipulate them with his gloved hands. Hand holds must be provided near each fastener to aid the astronaut in assembling the device. The types of latches and handles envisioned are shown on Figure 19.

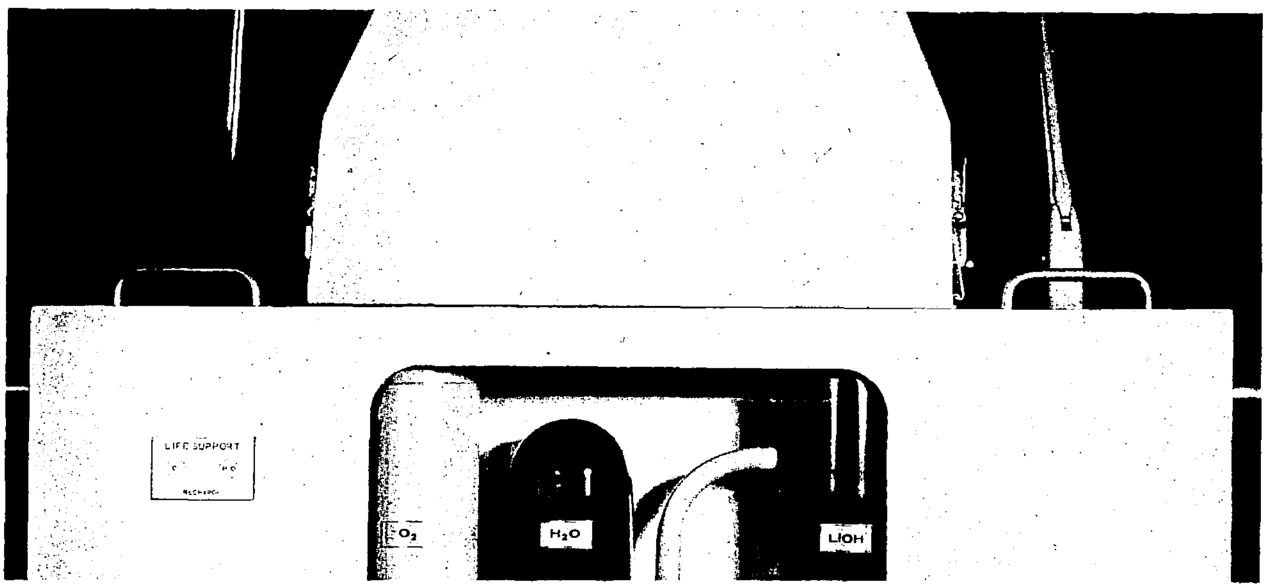


Figure 19. Fastening Mechanism and Associated Handhold

The work platform was designed around the use of a soft suit. A soft suit imposes certain limitations or restrictions to the astronaut's maneuverability and dexterity. Because of these restrictions it is of prime importance that controls and displays be positioned at optimum locations where they can be readily seen and controlled by the astronaut. The upper surface of the main module arms was deemed to be the best location. See Figures 20 through 23. The thruster and manipulator controls are integrated into the same handle. Switches located near the handles select the system being controlled. Other controls located on the main module include:

- Work site anchor controls
- T.V. positioning controls
- Communication
- Illumination
- Emergency release (e.g., work site anchors)
- Payload module
- Foot restraint locks
- Stabilization system

Displays would include the following:

- Lock engagement indicator lights (e.g., inter-module)
- Propulsion supply indicators
- Life support supply indicators

Displays necessary for long range guidance are incorporated into the long range guidance module.

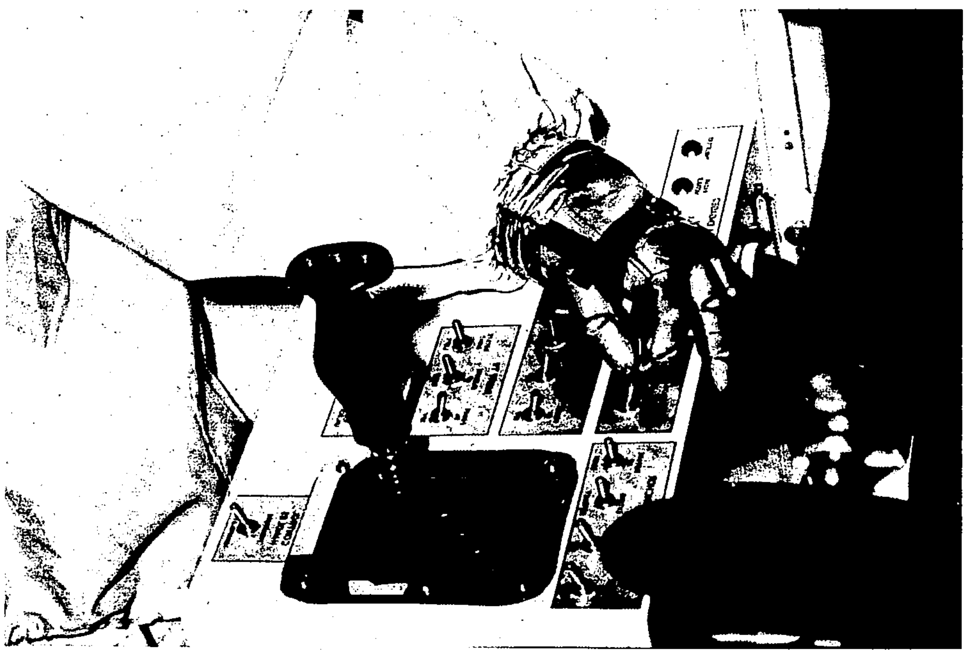


Figure 20. EVA Work Platform Controls and Displays

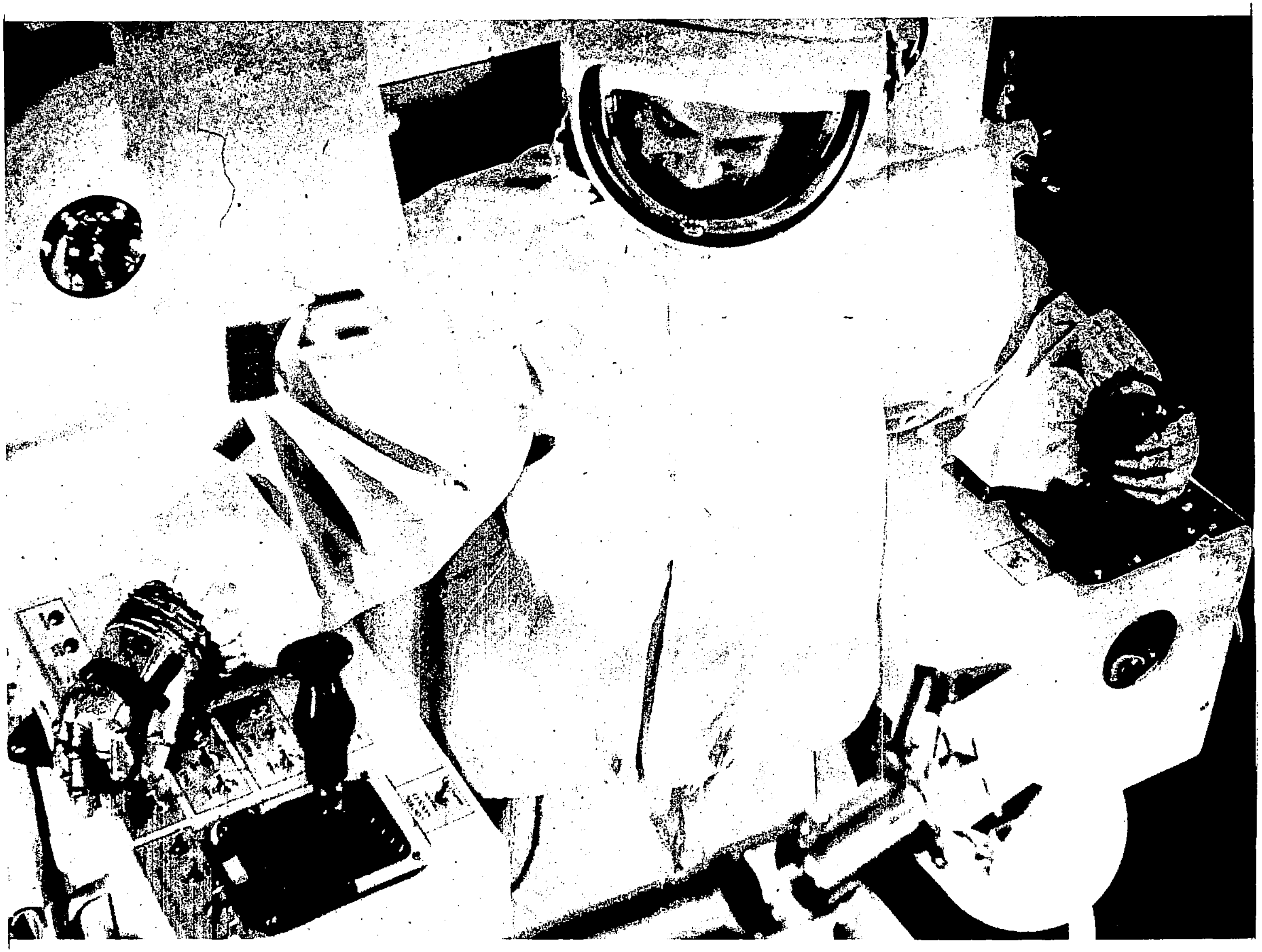


Figure 21. EVA Work Platform Controls and Displays

Figure 22. EVA Work Platform Controls and Displays

Figure 23. EVA Work Platform Controls and Displays

The following goals were used in the establishment of the size and shape of the platform:

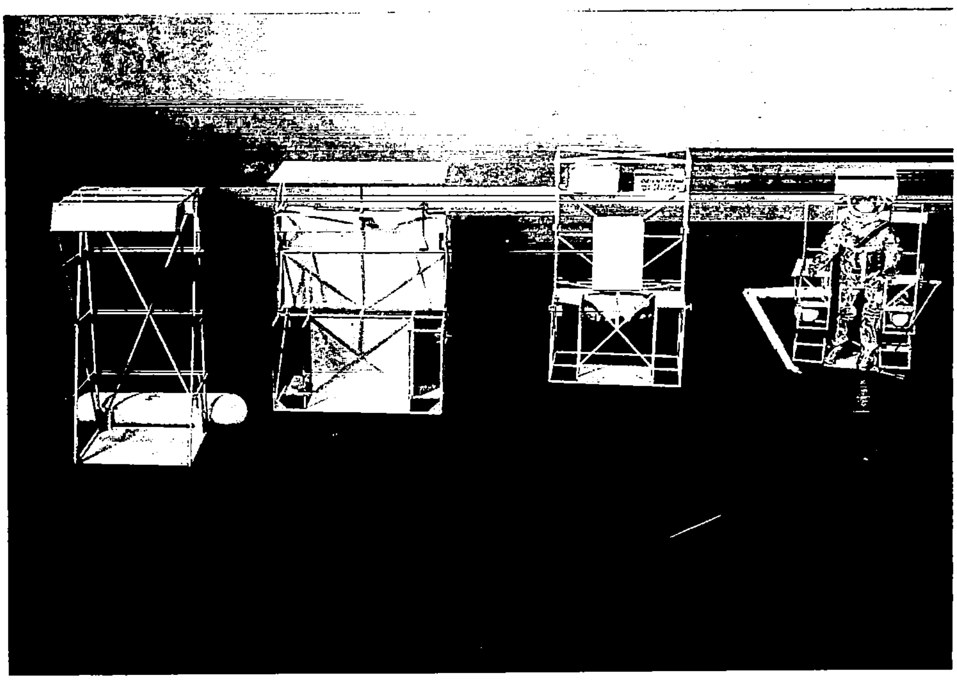
- Internal dimensions should be large to allow the astronaut freedom to choose an efficient working position
- External dimension should be small to:
  - allow maneuvering in tight quarters such as the inside of a telescope
  - to take up as little space in launch vehicle as possible
- Weight should be kept to a minimum for launch economy reasons
- Controls and displays should be readily accessible
- Astronaut's vision should be unobstructed
- Configuration must allow for easy entrance and exit from the platform

It was therefore concluded that the front of the platform should be open. Arms extending on each side of the astronaut would allow the controls to be positioned in front of and to the side of the astronaut where they are within ready vision and easy reach. An attempt was made to make the dimensions as small as possible without overly restraining the astronaut. Several configurations were considered before a final design was chosen. Evolution of the design is demonstrated by the one sixth scale models shown in Figure 24a. In the initial design, shown on the left, the structure itself was not modularized. Systems would be attached to a frame work as dictated by mission requirements. Methods of attachment would necessarily be simple so that systems could readily be added or subtracted in a weightless environment. In the second model "arms" were added for controls and the width of the platform increased. Tools would be available in bins located behind the astronaut. The width was decreased in the third model to satisfy customer requirements. The fourth model shown on the right and also in Figure 24b and Figure 24c is a design closely resembling the final configuration in which the structure itself is modularized.

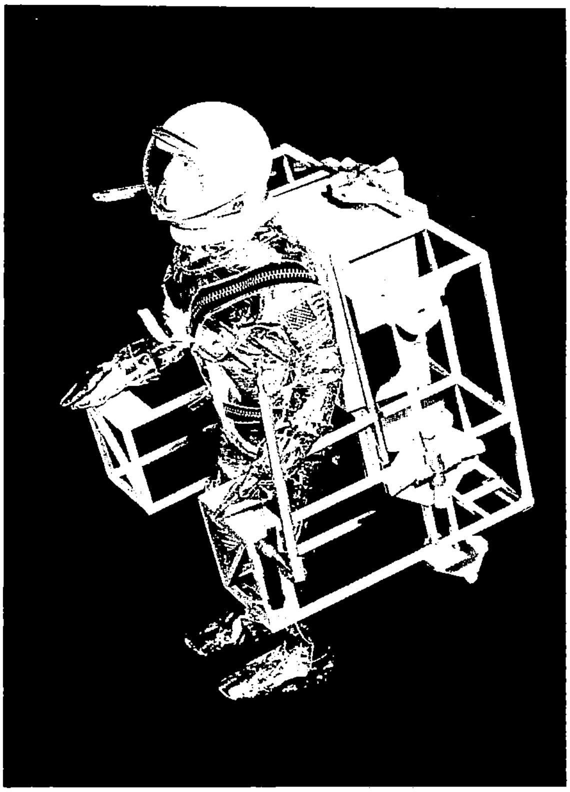
The dimensions of a pressure suited astronaut (Reference 14) were taken into account in establishing the final dimensions of the work platform and a full scale mockup was constructed to aid in the evaluation of the selected configuration. A Bendix Aerospace Systems Division human factors technician was utilized to try out the mockup while outfitted in a pressure suit. Time did not permit a thorough evaluation. The technician thought that with the following exceptions the choice of size and configuration was good:

- Switches on the thruster control handle were placed too close together.
- Switches located near the rear of the control panels were difficult to reach.
- Difficulty was experienced in reaching the instrument panel located on the Long Range Rendezvous Module.
- Interior width of main module was judged to be too small.
- Difficulty was experienced in placing his feet within the foot restraints. This was due to his lack of feel through the suit and lack of visual contact with the feet.

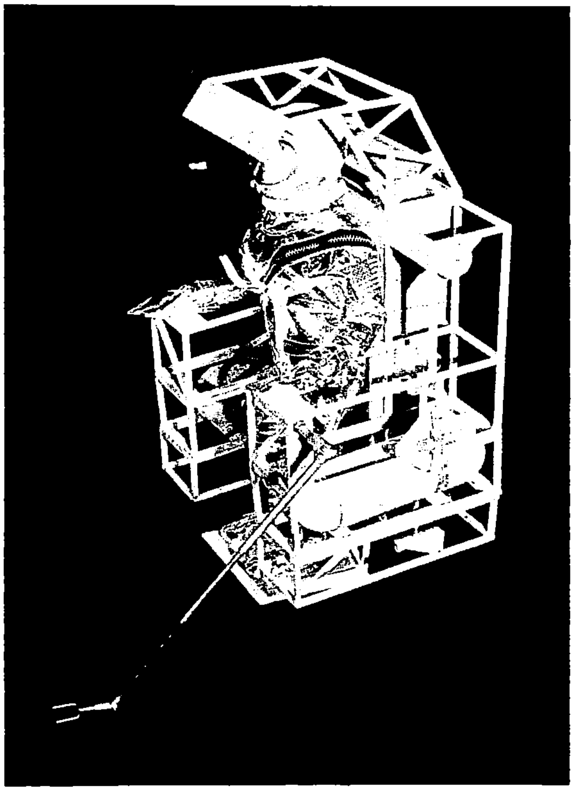
A Photograph of the suited technician in the work platform is given in Figure 25.



a.



b.



c.

Figure 24. Scale and Modules of Considered EVA Work Platform Configurations

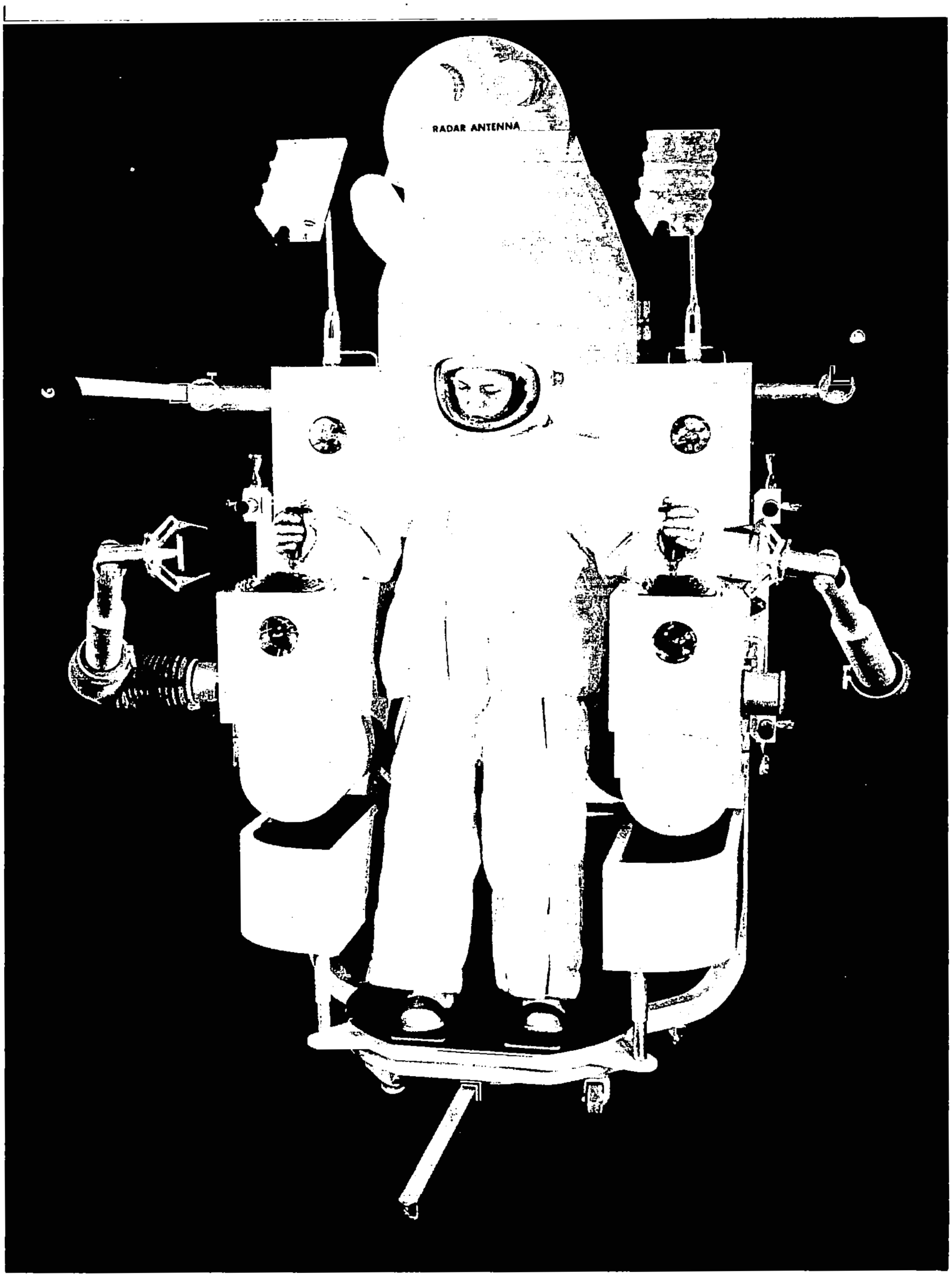


Figure 25. Astronaut in EVA Work Platform

Life Support

The open work platform concept allows the astronaut to leave the work platform, thus providing him with greater flexibility. To take full advantage of this feature, it was decided that the astronaut should wear a Portable Life Support System (PLSS) on his back for use when away from the platform rather than a long and cumbersome life support umbilical. An Apollo type PLSS was considered to be a satisfactory model for this study.

The Apollo PLSS provides oxygen for breathing and ventilation, maintains the oxygen purity, and controls the life support system temperatures. In addition it contains provisions that allow communication between the astronaut and his fellow crew members.

The PLSS primary oxygen bottle initially stores 1.03 pounds of oxygen at 1000 psia. Oxygen is fed automatically into the suit to maintain a pressure of 3.7 psia. The oxygen ventilating circuit subsystem removes carbon dioxide, humidity, and body gases and circulates purified oxygen at 7.9 pounds per hour by a battery powered fan. An audible warning will signal the astronaut with a tone, if the flow drops below 5 cubic feet per minute (6.3 pounds/hour).

The astronaut's suit incorporates a liquid cooled undergarment. Water is circulated through the garment to pick up the astronaut's metabolic heat and provide cooling through conduction. The PLSS water pump is also battery powered.

The heated water is cooled to 33^{o}F as it passes through a sublimator. The astronaut has a three position valve which can provide temperature roughly in the 45-50^{o}F, 60-65^{o}F, and 75-80^{o}F ranges by bypassing the sublimator during the recirculation process.

A PLSS feed water loop sends expendable water to the sublimator for the freezing and ejection process. A reservoir initially contains 6 pounds of water for this purpose.

An Apollo PLSS can support an astronaut for four hours. The work platform extends the operating time to 8 hours by supplying oxygen, lithium hydroxide (chemical used to remove CO_2) water and electrical power from the platform while the astronaut is on board. A recess is provided in the work platform to accommodate the PLSS. The recess is larger than the PLSS so as not to interfere with the astronauts activities. A short umbilical connects the PLSS to the platform supplies. A second umbilical connection is provided on the platform for possible use in rescue operations. When the umbilical is connected oxygen is routed through the work platform LiOH contamination control canister leaving the PLSS canister available for periods of operation away from the platform. The platform oxygen supply pressure regulator is set at a slightly higher value than the PLSS regulator so that all makeup oxygen is supplied from the work platform bottle until that supply is expended. Similarly, the water supply system is designed so that the platform water is used first.

The platform life support system is located directly behind the PLSS recess in the main module. (See Figure 26). The oxygen and water bottles can be recharged by the mother ship for repeated use. The lithium hydroxide canisters can be replaced as required.

The amount of consumables required aboard the platform is determined by the average metabolic rate of an astronaut over a four hour period. It is estimated that approximately one pound of oxygen and six pounds of water will be satisfactory. Total weight of the platform life support system is estimated at 30 pounds.

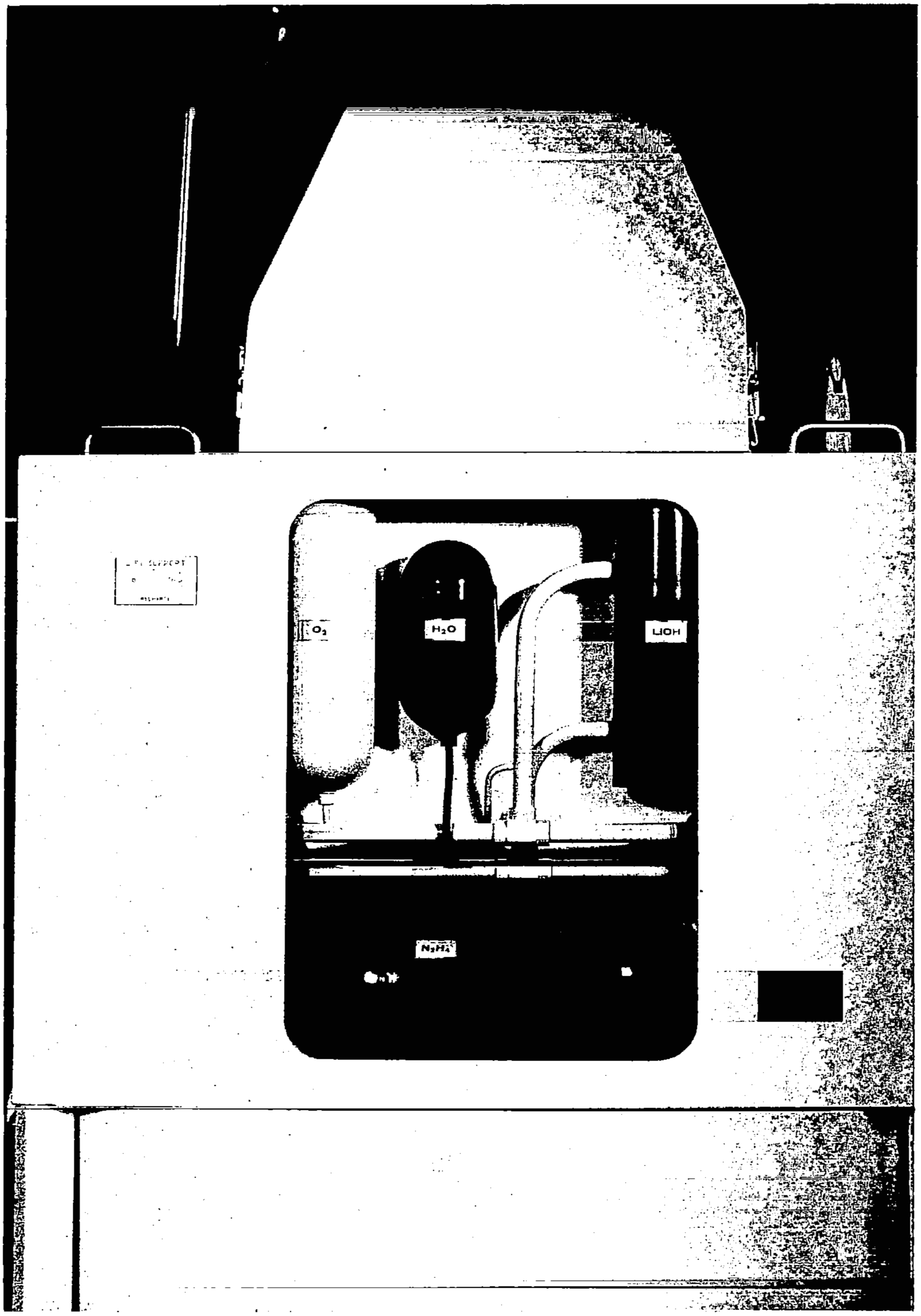


Figure 26. Life Support Consummables and Fuel Tank

Electrical Power

Considering the fact that the work platform will always be used as a companion of and as a supplement to a much larger permanent orbiting station, work platform electrical requirements are best satisfied by storage means rather than on-board generation. The permanent station will logically have electrical power generation facilities (nuclear, solar, fuel cell, etc.) of sufficient capacity to supply the long term needs of itself as well as supplementary objects such as the work platform.

Three types of rechargeable storage batteries; silver zinc, silver-cadmium, and nickel cadmium, were considered for supplying the work platform power. The silver zinc battery was tentatively selected because of its high energy to weight ratio. Typical energy to weight ratios for silver zinc batteries range from 30 to 60 watt-hours per pound compared to 25-33 watt hours per pound for silver cadmium batteries and 10-15 watt-hours per pound for nickel cadmium batteries. The energy to weight ratio is dependent upon a number of factors including discharge rate, operating temperatures and number of operating cycles.

The depth of discharge limits the number of times a battery can be recharged. A comparison fo the cycling capabilities of the three types of batteries considered was obtained from reference 24. This information is presented on Figure 27. For a depth of discharge of 75 percent the silver zinc battery is limited to 75 cycles compared to 100 for the silver cadmium battery and 1000 for the nickel cadmium battery. For a 50 percent depth of discharge these values are increased to 400, 750, and 3500 cycles respectively. If the work platform requirements are such that it is frequently in use and therefore requiring many charging-discharging cycles of its battery, the silver cadmium or the nickel cadmium battery may be a better choice. The nickel cadmium battery has a serious disadvantage, however, in that it loses its charge during stowage. The self discharge rates are on the order of 20 to 30 percent of capacity in as little time as a week at temperatures much above room ambient (Reference 25).

The battery located in the main module will supply all the electrical power required by the main module plus electrical power to the PLSS when the astronaut is aboard the platform. Power required by the other modules will be provided by independent batteries packaged in these modules.

A brief discussion of the main module power requirements follows.

Electrical power required by the propulsion system may range from 2 to 30 watts per thruster, depending upon the final design of the solenoid valve which controls the fuel to this combustion chamber. Valve operation time is calculated as follows:

$$\text{Time} = \frac{I_{sp}\, W_p}{T}$$

where: I_{sp}, fuel specific impulse = 190 seconds
W_p, total fuel weight = 200 pounds
T, thrust per engine = 6 pounds

$$\text{Time} = \frac{190 \cdot 200}{6} = 6333 \text{ seconds} = 1.76 \text{ hours}$$

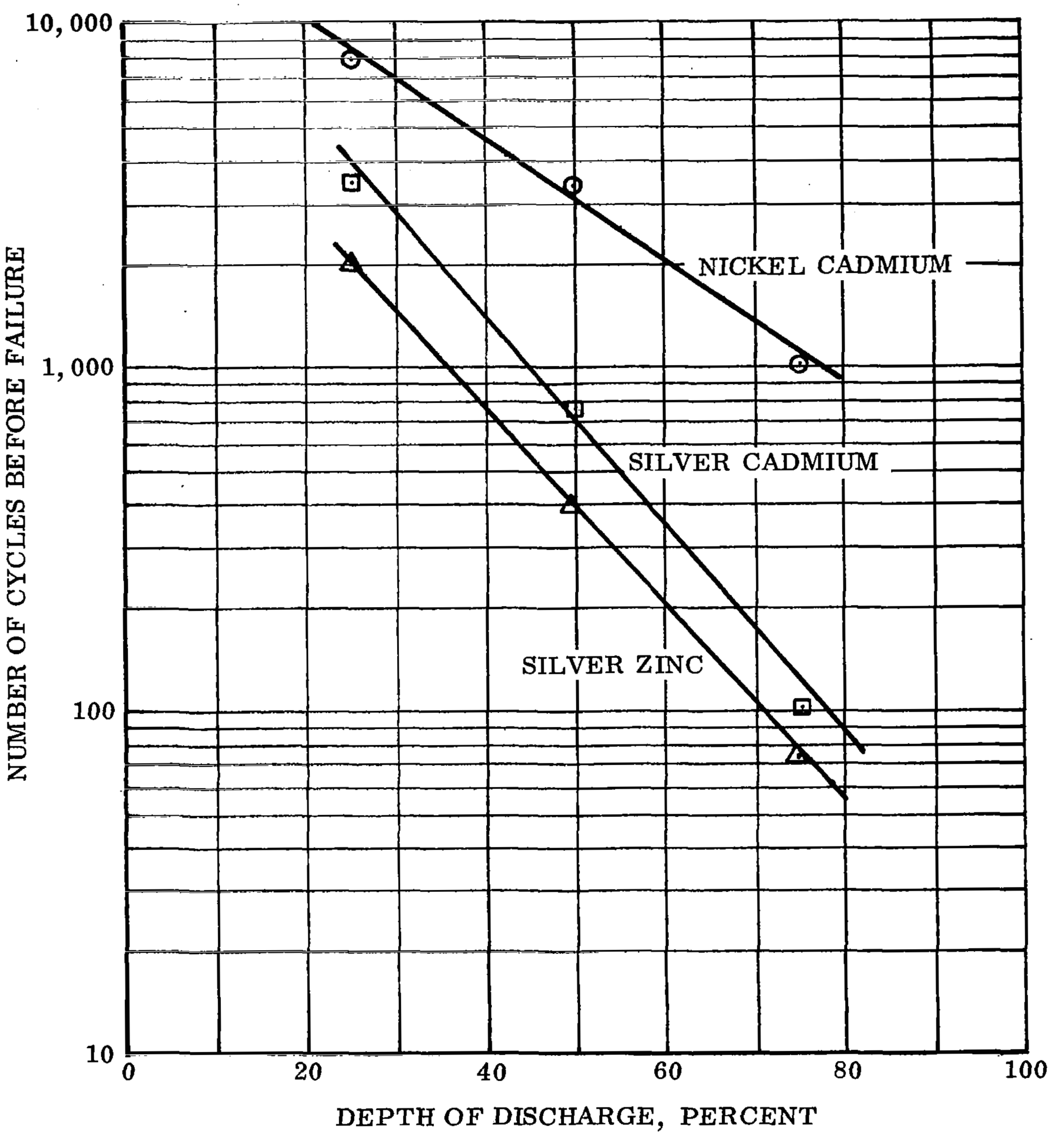


Figure 27. State-of-Art Cycling Capability

Assuming a 25 watt solenoid, the electrical energy required for the mission equals 1.76 x 25 = 44 watt-hours.

It is assumed that the communication system will need 30 watts. This includes 6 watts for each television camera. Total energy for 8 hours of operation is 240 watt-hours.

The PLSS requires 60 watts of electrical power. A battery within the PLSS can supply this power for four hours. To extend the life support capabilities to 8 hours, the EVA work platform must be capable of providing an additional 240 watt-hours.

The gyros are rated at 11.5 watts and will require 92 watt-hours of energy over an 8 hour period.

Argonne National Laboratory estimates that 664 watt-hours of energy will be required for manipulator system operation during a four hour work period. The task profile on which this estimate is based is given in Table 3, for a one hour work period. The profile is based on experienced gained in hot laboratory operations and on considerations of tasks to be done in space. Not shown in the table is 5 watt-hours allotted for indexing operations.

TABLE 3. TASK PROFILE FOR EACH MANIPULATOR

Force at slave "hands" (lbs)	Velocity at slave hands (in/sec)	Force at master handle (lbs)	Power required for one motion (watts)	Power required for one manipulator (watts)	Time at force noted (min)	Energy required per manipulator for time shown (watt-hour)
25	5	12.5	142	359	2	12.0
8	20	4.0	60	195	9	29.2
1	30	0.5	21	117	10	19.5
0	0	0 (Brakes off)	15	105	10	17.5
0	0	0 (Brakes on)	0	0	29	0
				Totals	60	78.2

Power consumptions used to size the battery are summarized in Table 4.

TABLE 4. ELECTRICAL POWER CONSUMPTION

System	Ave. Power Watts	Time Hours	Energy Watt-Hours
Propulsion	25	1.76	44
Communications	30	8	240
Gyros	11.5	8	92
PLSS Supplement	60	4	240
Illumination			136
Manipulators	166	4	664
All Other			135
		Total	1551

A 2400 watt-hour, 60 pound silver zinc battery was tentatively selected to provide this energy. The 1551 watt-hour figure represents a depth of discharge of 65 percent. The battery should be capable of 145 discharge cycles of this magnitude. Most missions will use considerably less energy than this, however, and a corresponding increase in the number of cycles can be expected.

Typical Yardney Electric Corporation silver zinc cell performance curves are presented on Figure 28.

Thermal Control

Heat is produced as a by-product of the dissipation of electrical power. For example, it is estimated that nearly all of the electrical power supplied to the manipulator systems is expended in heat. It is important that this heat be continuously transferred to space to maintain satisfactory equilibrium temperatures. Either a radiator or a sublimator could be used for this purpose. A water fed sublimator similar to that used in the PLSS appears to be the better choice. The components requiring cooling would be mounted on "cold plates". Coolant would be circulated continuously between the "cold plates" and the sublimator to maintain a satisfactory temperature.

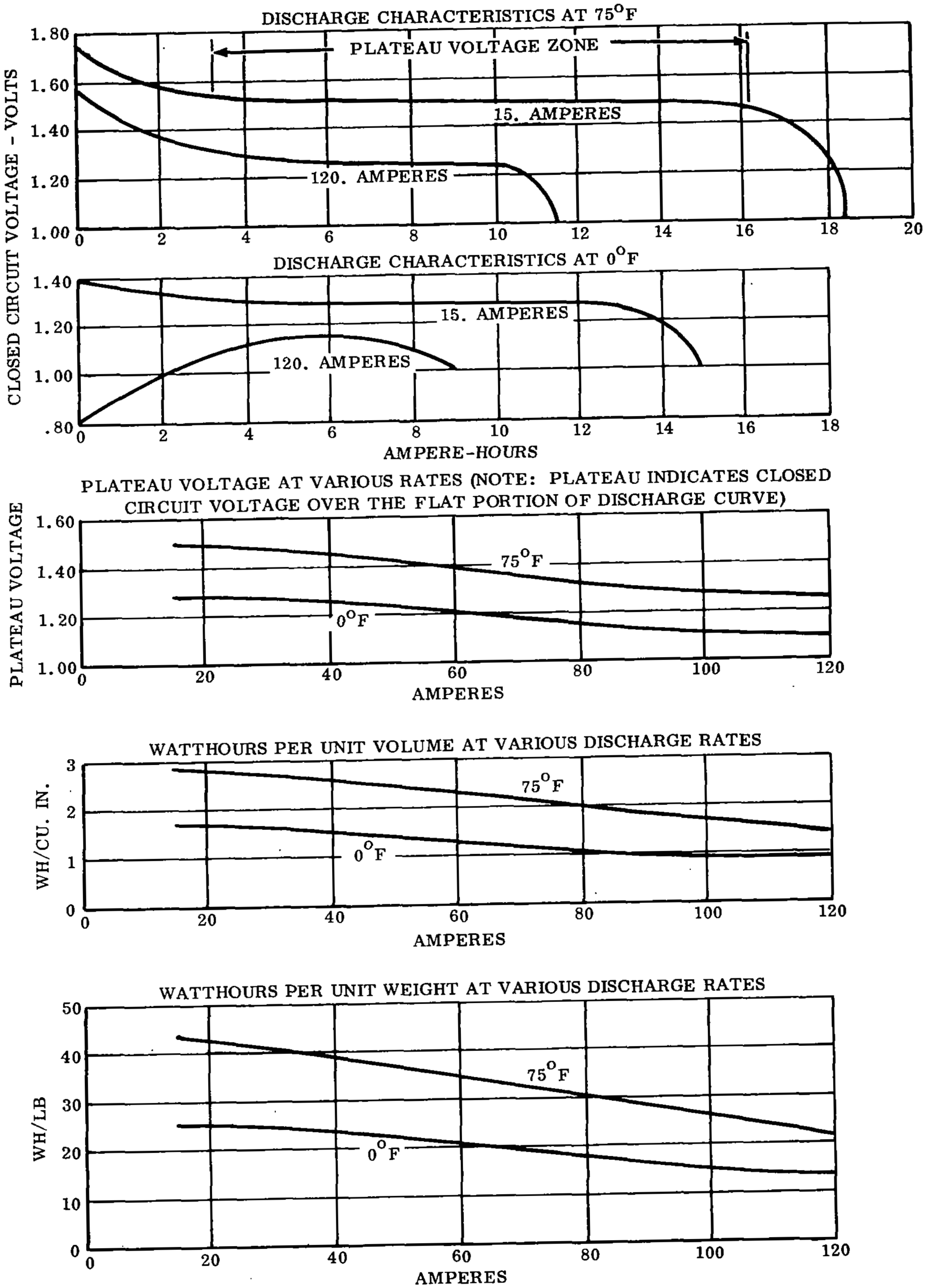


Figure 28. Typical Silver-Zinc Cell Performance Curves

Maintaining proper temperature of the hydrazine fuel may also be a problem. A brief study was performed to determine the average bulk temperature of the fuel. Results of this study are given in SEM 4701 which is included as Appendix A of this report. It was concluded that fuel tank surface radiation properties could be selected to provide passive thermal control. However, it was decided that a more positive control of the temperature was desirable. A surface absorptivity to emissity ratio that tends to cool the fuel temperature would be selected and small heaters will be used to regulate the temperature at the desired level.

Sizes

Weight-volume estimates of the EVA work platform are given in Table 5. The estimates are primarily based upon literature reviewed during the course of the study. In some cases allowances have been made for advances in the state of the art since similar existing systems were designed. The platform radar system, for example, was based upon the GEMINI Rendezvous Radar which weighed 72.15 pounds. It is now feasible to design the radar using monolithic integrated circuitry in many areas and smaller and lighter components in other areas with a significant decrease in weight and volume. A Westinghouse Electric Company memorandum dated January 11, 1966 details how the Gemini Radar weight could be reduced to 40 pounds. Similarly the transponder weighing only 25 pounds could be developed for the work platform. The Gemini transponder weighed 41.39 pounds.

The weight and volume given for the manipulator system should be considered as being a very rough estimate. Manipulator systems have never been developed for use in space, although several studies have been conducted concerning their use in space. Heavy counterweights needed for ground base manipulators are not needed under zero g conditions. The servo motors and electronic amplifiers can be miniaturized for space applications. Details of this miniaturization, to our knowledge, have not been completely evaluated.

The weight of the tool module will vary with mission requirements. The module equipped with a Martin Tool Kit is estimated at 50 pounds.

TABLE 5. EVA WORK PLATFORM WEIGHT/VOLUME ESTIMATES

SYSTEM	Weight Lbs.	Volume In.^{3}
Main Module and Astronaut		
Astronaut and Suit	200	
PLSS	65	2430
Communications, (Radio & T.M.)	15	374
Two T.V. Cameras	14	412
Additional 4 hours Life Support:		
Oxygen System	6	300
Water System	10	175
Lithium Hydroxide Canister	13	285
2400 Watt-Hours Silver Zinc Battery	61	850
Stabilization System	15	375
Two Electrical Bilateral Manipulators	485	17800
16 Thrusters Fuel Lines and Valves	20	
50 lbs. Fuel and Tank	56	1380
Nitrogen Tank and N_2	5	125
Frame	30	
Transponder and Antenna	25	1040
Miscellaneous (docking devices, cooling systems, lighting provisions, etc.)	32	
Total	1052	
Extended Propulsion Capability		
Two, 75 lb. Fuel Tanks	164	4170
Two Nitrogen Tanks	12	360
Supports, Lines, Valves, etc.	3	
Total	179	

TABLE 5. EVA WORK PLATFORM WEIGHT/VOLUME ESTIMATES (Continued)

SYSTEM	Weight
Long Range Rendezvous Module	
Antenna Assembly	4.1
Servo Assembly	5.6
R. F. Assembly	3.0
Receiving System	.5
Transmitter Assembly	1.1
Digital Assembly	1.9
Video Circuits	1.4
Servo Amplifier	0.6
Power Supply	5.0
TLM Transducers	0.2
Ground Plane	6.2
Modulator	0.3
Frame and R. F. Deck	1.5
Pressure Vessel	3.4
Connectors	1.2
Miscellaneous	2.0
Cables	2.0
Total Radar	40 pounds
Computer	18
Battery	5
Displays and Frame	10
Total	73 pounds

SECTION 5

BIBLIOGRAPHY

1. Study of Extravehicular Protection and Operations, P. Iribe, J. A. Lieske, John Hopkins University, Applied Physics Laboratory, TG-841 July 1966.

2. Orbital Extravehicular Mockup Design, P. Iribe, John Hopkins University, Applied Applied Physics Laboratory, TG-957 January 1968.

3. Apollo Lunar T.V. Camera, (Brochure) Westinghouse Defense and Space Center, Aerospace Division, Baltimore, Maryland (Ref. Contract NAS 9-3548).

4. Conference Proceedings of National Conference on Space and Extravehicular Activities, Orlando, Florida March 1966.

5. Gemini Midprogram Conference, including Experiment Results, NASA SP-121, February 1966.

6. A Collection of Papers on Space Suits and Human Performance, Chrysler Corporation, Space Div., New Orleans, Louisiana; Edited by Norman M. Molesko; August 16, 1965; REL-HFG-65-1.

7. Technical Memorandum for Improved Gemini Radar, Westinghouse Electric Corporation, Aerospace Div., Baltimore, Maryland; January 11, 1966.

8. Pre-Phase 1 Study for the MOL P-6 Extravehicular Activity (EVA) Experiment-Volume 1, Robert Garnett, Roger Walker, etal, Ling Temco Vaught; AFAPL-TR-64-145, December 1964.

9. Designer's Checklist Hydrazine Monopropellant Rockets and Gas Generators, Rocket Research Corp., Seattle, Washington.

10. Monopropellant Hydrazine Propellant Systems, an Engineering Study, 65-ES-28R; Rocket Research Corp., Seattle, Washington; October 20, 1965.

11. Space Maneuvering Systems; (Brochure Circa 1965) LTV, Astronautics Div.

12. Proceedings of the 12th Conference on Remote Systems Technology, "Manipulator Systems Development at ANL", Ray Goertz, Argonne National Lab., November, 1964.

13. AEC/ANL Manipulator Consulting Support to Ling-Temco-Vought Inc. and the Marshall Space Flight Center, Argonne National Laboratory.

14. Bioastronautic Data Book, NASA SP-3006, Paul Webb, M.D., Editor.

15. Analytical Methods for Space Vehicle Atmospheric Control Processes, Technical Report No. ASD-TR-61-162, Part II; November 1962; Flight Accessories Laboratory Aeronautical Systems Div., Air Force Systems Command, Wright-Patterson AFB, Ohio.

16. Fuel Cell Power Systems Weight Analysis, John M. Thielman, Boeing Co., May 1962; (Society of Aeronautical Weight Engineers Inc., Paper, No. 324).

17. Feasibility of a Self-Maneuvering Unit for Orbital Maintenance Workers, S.M.U. Technical Documentary Report ASD-TDR-62-278, August 1962, by Change-Vought Corp., Dallas, Texas, for the USAF Aeronautical Systems Division, Wright-Patterson A.F.B., Ohio.

18. Space Tool Kit Survey, Development and Evaluation Program Final Report, Martin Report No. ER 13942 prepared under NASA Contract NAS 9-3161, by The Martin Company, Baltimore, Maryland.

19. Maintenance in a Weightless Environment, Chester May, Air Force Aero Propulsion Lab., Wright-Patterson AFB, Ohio, April 1965. (American Institute of Aeronautics and Astronautics Paper No. 65-257).

20. Survey of Remote Handling in Space, D. Fredrick Baker, 1st Lt. USAF (Compiler), Technical Documentary Report AMRL-TDR-62-100 September 1962, Wright-Patterson AFB, Ohio.

21. Design and Development of the Apollo Extra-Vehicular Mobility Unit, J. C. Beggs, Hamilton Standard Division of United Aircraft Corp., TP65-01, January 1965.

22. "Design Verification Under Way on Apollo Suit Backpack," Aviation Week, December 13, 1965, page 52.

23. "Lunar Astronauts to Use New Oxygen Pack," Aviation Week and Space Technology, June 3, 1968, page 76.

24. Sealed Nickel-Cadmium Batteries for Aircraft Electrical Systems, Gerald H. Miller, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base; Presented at the IEEE Aerospace Systems Conference July 11-15, 1966 in Seattle, Washington.

25. Development of an Electrochemical Energy Source for the Mariner II Spacecraft, Charles W. Brooks, Jr. Jet Propulsion Laboratory, California Institute of Technology, Pasadena California, Technical Report 32-854 dated March 15, 1966.

NASA-Langley, 1969 —— 11 CR-1361